Renewable and Sustainable Energy Reviews 18 (2013) 211–245

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production

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ARTICLE INFO

Article history:
Received 3 February 2012
Received in revised form
7 October 2012
Accepted 9 October 2012
Available online 13 November 2012

Keywords:
Biodiesel
Non-edible oil feedstocks
Oil extraction
Fatty acid compositions
Physical and chemical properties
Engine performance and emissions production

ABSTRACT

World energy demand is expected to increase due to the expanding urbanization, better living standards and increasing population. At a time when society is becoming increasingly aware of the declining reserves of fossil fuels beside the environmental concerns, it has become apparent that biodiesel is destined to make a substantial contribution to the future energy demands of the domestic and industrial economies. There are different potential feedstocks for biodiesel production. Non-edible vegetable oils which are known as the second generation feedstocks can be considered as promising substitutions for traditional edible food crops for the production of biodiesel. The use of non-edible plant oils is very significant because of the tremendous demand for edible oils as food source. Moreover, edible oils' feedstock costs are far expensive to be used as fuel. Therefore, production of biodiesel from non-edible oils is an effective way to overcome all the associated problems with edible oils. However, the potential of converting non-edible oil into biodiesel must be well examined. This is because physical and chemical properties of biodiesel produced from any feedstock must comply with the limits of ASTM and DIN EN specifications for biodiesel fuels. This paper introduces non-edible vegetable oils to be used as biodiesel feedstocks. Several aspects related to these feedstocks have been reviewed from various recent publications. These aspects include overview of non-edible oil resources, advantages of non-edible oils, problems in exploitation of non-edible oils, fatty acid composition profiles (FAC) of various non-edible oils, oil extraction techniques, technologies of biodiesel production from non-edible oils, biodiesel standards and characterization, properties and characteristic of non-edible biodiesel and engine performance and emission production. As a conclusion, it has been found that there is a huge chance to produce biodiesel from non-edible oil sources and therefore it can boost the future production of biodiesel.

Contents

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http://dx.doi.org/10.1016/j.rser.2012.10.013

1. Introduction

The declining reserves of fossil fuels and the growing environmental concerns have made renewable energy an exceptionally attractive alternative energy source for the future [1,2]. Biodiesel is one of these promising alternative resources for diesel engines. It is defined as the mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats and alcohol with or without a catalyst. It is renewable, biodegradable, environmentally friendly, non-toxic, portable, readily available and eco-friendly fuel [3–6]. There are different potential feedstocks for biodiesel production. The use of edible vegetable oils or the first generation feedstocks has been of great concern recently; this is because they raise many concerns such as food versus fuel debate that might cause starvation especially in the developing countries and other environmental problems caused by utilizing much of the available arable land. This problem can create serious ecological imbalances as countries around the world began cutting down forests for plantation purposes. Hence, use of these feedstocks could cause deforestation and damage to the wildlife. Therefore, non-edible vegetable oils or the second generation feedstocks have become more attractive for biodiesel production. These feedstocks are very promising for the sustainable production of biodiesel. Some examples of non-edible oilseed crops are *Jatropha curcas*, *Calophyllum inophyllum*, *Sterculia feotida*, *Madhuca indica* (mahua), *Pongamia glabra* (koroch seed), *Linseed*, *Pongamia pinnata* (karanja), *Hevea brasiliensis* (Rubber seed), *Azadirachta indica* (neem), *Camelina sativa*, *Lesquerella fendleri*, *Nicotiana tabacum* (tobacco), *Deccan hemp*, *Ricinus communis* L. (castor), *Babassu*, *Simmondsia chinensis* (Jojoba), *Eruca sativa.* L.,

Cerbera odollam (Sea mango), Coriander (*Coriandrum sativum L.*), *Croton megalocarpus*, *Salmon oil*, *Pilu*, *Crambe*, *syringa*, *Scheleichera triguga* (kusum), *Stillingia*, *Shorea robusta* (sal), *Terminalia belerica roxb*, *Cuphea*, *Camellia*, *Champaca*, *Simarouba glauca*, *Garcinia indica*, Rice bran, *Hingan* (balanites), *Desert date*, *Cardoon*, *Asclepias syriaca* (Milkweed), *Guizotia abyssinica*, *Radish Ethiopian mustard*, *Syagrus*, *Tung*, *Idesia polycarpa* var. vestita, *Alagae*, *Argemone mexicana L.* (Mexican prickly poppy, *Putranjiva roxburghii* (*Lucky bean tree*), *Sapindus mukorossi* (Soapnut), *M. azedarach* (syringe), *Thevettia peruviana* (yellow oleander), Copaiba, Milk bush, Laurel, Cumaru, Andiroba, Almond, Piqui, *B. napus*, Tomato seed, *Zanthoxylum bungeanum* etc. [1–4,6–32]. Moreover, microalgae which is regarded as the third generation feedstock, has become the latest potential inexhaustible source of biodiesel. Microalgae are very economical as compared to edible oils. It was reported that microalgae has the highest oil yield compared to other oil crops [33]. Microalgae with high oil content have the potential to produce an oil yield that is up to 25 times higher than the yield of traditional biodiesel crops, such as oil palm. This plant, with an oil production of at least 70% oil by weight of dry biomass, requires only 0.1 m^2 year per kg biodiesel of land to produce 121,104 kg of biodiesel per year. This large production value is one of the reasons that microalgae have been recognized as a potentially good source for biodiesel production, which a process previously was dominated by palm oil [6]. Other feedstock for biodiesel is waste cooking vegetable oils, which have been considered a promising option with relative cheap price for biodiesel production in comparison with fresh vegetable oil. Biodiesel from used cooking oil is one option of the economical sources for biodiesel production [1,34]. However, it must be pointed out that global biodiesel feedstocks should not rely on certain sources as it could bring harmful influence in the long run. The worlds' dependence on fossil fuels is a perfect example. Therefore, biodiesel feedstock should be as diversified as possible, depending on geographical locations in the world.

The aim of this paper is to present the potential of non-edible vegetable oils for biodiesel production that can replace the current dependence on the edible oil resources worldwide. Several related aspects to these feedstocks have been reviewed from various recent publications. These aspects included overview of non-edible oil resources, advantages of non-edible oils, problems in exploitation of non-edible oils, fatty acid composition profiles (FAC) of various non-edible oils, oil extraction techniques, technologies of biodiesel production from non-edible oils, biodiesel standards and characterization, properties and characteristics of non-edible biodiesel and engine performance and emission productions.

2. Non-edible vegetable oils resources

Non-edible vegetable oils are not suitable for human food due to the presence of some toxic components in the oils [6]. The selection of non-edible vegetable oils as feedstocks for biodiesel production requires reviewing the existing works. Recent comprehensive reviews on biodiesel production from various feedstocks show the advantages of non-edible oils over edible oils. Production of biodiesel from non-edible oils feedstocks can overcome the problems of food verse fuel, environmental and economic issues related to edible vegetable [35]. Moreover, Non-edible biodiesel crops are expected to use lands that are largely unproductive and those that are located in poverty-stricken areas and in degraded forests. They can also be planted on cultivators' field boundaries, fallow lands, and in public land such as along railways, roads and irrigation canals. Non-edible biodiesel development could become a major poverty alleviation program for the rural poor apart from providing energy security in general and to rural areas in particular and upgrading the rural non-farm sector. All of these issues have a great impact on the sustainability of biodiesel production. Many researchers have concluded that non-edible feedstocks of biodiesel should be considered as sustainable and alternative fuels [6,36,37].

Non-edible oil plants are well adapted to arid, semi-arid conditions and require low fertility and moisture demand to grow. Moreover they are commonly propagated through seed or cuttings. Since these plants do not compete with food, seed cake after oil expelling may be used as fertilizer for soil enrichment [16]. Several potential tree borne oil seeds (TBOs) and non-edible crop source have been identified as suitable feedstock for biodiesel [36,38,39]. Table 1 shows the list of potential tree borne oil seeds (non-edible oils) for biodiesel production. A collection of some potential non-edible sources for biodiesel industry is shown in Fig. 1. In the following section, a brief description of various types of non-edible plant oils will be presented.

2.1. *Jatropha curcas L.*

Jatropha curcas L. is a small tree or large shrub, up to 5–7 m tall, belonging to the Euphorbiaceae family [24,36,40–44]. It is a drought-resistant plant capable of surviving in abandoned and fallowed agricultural lands [24–26,40,45]. It is a tropical plant that is able to thrive in a number of climatic zones with rainfall of 250–1200 mm. The plant is native to Mexico, Central America, Africa, India, Brazil, Bolivia, Peru, Argentina and Paraguay [16,24,26,36,44,46]. It is well adapted in arid and semi-arid conditions and has low fertility and moisture demand. It can also grow on moderately sodic and saline, degraded and eroded soils. The ideal density of plants per hectare is 2500. It produces seeds after 12 months and reaches its maximum productivity by 5 years and can live 30–50 years. Seed production ranges from 0.1 $tha^{-1}\,yr^{-1}$ to more than 8 $t\,ha^{-1}\,yr^{-1}$depending on the soil conditions [16,24]. Depending on variety, the decorticated seed of *Jatropha* contain 43–59% of oil [2].

2.2. *Pongamia pinnata L. (Karanja)*

Pongamia pinnata (L.) Pierre (karanja or honge), an arboreal legume is a medium sized evergreen tree belonging to the family (Legumnosae; Pappilonaceae), more specifically the Millettieae tribe, which grows in Indian subcontinent and south-east Asia and has been successfully introduced to humid tropical regions of the world as well as parts of Australia, New Zealand, China and the USA [25,47,48]. A single tree is said to yield 9–90 kg seeds, indicating a yield potential of 900–9000 kg seed/ha (assuming 100 trees/ha) [47]. It is one of the few nitrogen fixing trees (NFTS) that produce seeds with a significant oil content [35,49]. The plant is fast growing, drought resistant, moderately frost hardy and highly tolerant of salinity. It can be regenerated through direct sowing, transplanting and root or shoot cutting. Its maturity comes after 4–7 years. Historically, this plant has been used in Indian and neighboring regions as a source of traditional medicines, animal fodder, green manure, timber, water-paint binder, pesticide, fish poison and fuel. Recently, *Pongamia pinnata* has been recognized as a viable source of oil for the burgeoning biofuel industry. The tree may be planted with a spacing of 3×3 m^2 [16,26,36,48,50,51]. The seed oil content ranges between 30 and 40 wt% [7,16,27,47]. The oil is reddish brown and rich in unsaponifiable matter and oleic acid [51].

2.3. *Croton megalocarpus*

Croton megalocarpus is a member of the Euphorbiaceae family. It is a dominant upper canopy forest tree with heights ranging

Table 1
Non-edible sources of vegetable oil.

Non-edible vegetable source	Distribution	Plant type	Plant part	Oil content		Yields of various plant oils		Uses	Refs.
				Seed (wt%)	Kernel (wt%)	kg oil/ha	liters oil/ha		
Azadirachta indica (neem)	Native to India, Burma, Bangladesh, Sri Lanka, Malaysia Pakistan and Cuba, growing in tropical and semitropical regions	Tree	Seed, kernel	20–30	25–45	2670	–	Oil-illuminant, timber, firewood, biodiesel	[2,4,16,39,50,72,189,190]
Aphanamixis piolystachya (wall.) Parker	Growing in India, China	Tree	Kernel	–	35	–	–	Oil-illuminant	[38,39,191]
Annona muricata	The Caribbean and Central America but now growing in tropical climates throughout the world	Tree	Seed	–	20–30	–	–	Oil	[189,192,193]
Annona squamosa	Caribbean, Central America, Northern South America, Western South America, Southern South America, Pacific, Australasia, Indomalaya	Tree	Seed	15–20	–	–	–	Oil, biodiesel	[189,193]
Aleurites trisperma	Cuba	Tree	Kernel	–	–	–	–	Candels shaped from the paste of kernels used for illuminations ,kernels yield oil-illuminant	[39,194]
Asclepias syriaca (milkweed)	Distributed to the northeast and north-central United States	Herbaceous perennial	Seeds	20–25	0.019	–	–		[2,25,38,50,145]
Barringtonia racemosa Roxb. (L.) Spreng.	Widely spread in East Africa, Southeast Asia and the Pacific islands	Tree	Seed	–	–	–	–	Oil-illuminant used in lamps	[39,195]
Brassica carinata (ethiopian mustard)	Ethiopia	Herbaceous annual	Seed, kernel	42	2.2–10.8	–	–		[2,25]
Balanites aegyptiaca (desert date)	Growing in arid regions in Africa and Asia	Tree	Kernel		36–47	–	–	Oil, biodiesel	[39,142,191]
Bombax malabaricum	India	Tree	Seed	18–26	–	–	–		
Calophyllum inophyllum L.	Tropical regions of India, Malaysia, Indonesia, and the Philippines.	Tree	Seed, kernel	65	22	4680	–	Oil used for burning, timber	[4,16,25,36,38,39,104,136,190,196]
Crambe abyssinica	Mediterania, Eithiopia, Tanzania, East of Africa, Italia, Argentina	Herb	Seed	30–38	–	1129	–	Oil, lubricant	[2,39,197,198]
Ceiba pentandra	Native to Mexico, Central America and the Caribbean, northern South America, and (as the variety *C. pentandra* var. *guineensis*) to tropical west Africa, Indonesia (Java)	Tree	Seed	24–40	–	–	–	Timber, oil	[189,190]
Cerbera odollam (sea mango)	Native to India and other parts of Southern Asia	Tree	Seed, kernel	54	6.4	–	–	Illuminant (release thick smoke)	[2,10,90]
Croton tiglium	China, Malabar, Ceylon, Amboina (of the Molucca islands), the Philippines and Java	Herbaceous perennial	Seed, kernel	30–45	50–60	–	–	Biodiesel, resin, oil	[16,39,189,191,199]
Cuphea	The eastern United States, North-central USA to Argentina	Herbaceous annual	Seed	20–38	–	900	–	Biodiesel	[94–97,200]
Crotalaria retusa L. (fabaceae)	Native in Asia, Coastal Eastern and Africa	Herbaceous annual	Seed	15	–	–	–	Oil, biodiesel	[201]
Eruca sativa gars	Northwest of China, South Asia	Herbaceous perennial	Seed	35	–	420–590	–		[14,39,98]
Garcinia indica	Tropical rain forests of Western Ghats, Konkana, North Kanara, South Kanara, Bombay, Goa and Coorg	Tree	Seed	45.5	–	–	–	Biodiesel, resin, oil	[2,16,17]
	Cultivated in Ethiopia and India		Seed	50–60	–	200–300	–	Commercial oil, biodiesel	[18,202]

Guizotia abyssinica L. (niger)		Herbaceous annual							
Hevea brasiliensis (rubber)	Grow in Nigeria, India, Brazil, Southeast Asia, West Africa	Tree	Seed	40–60	40–50	50	–	Surface coatings including paints, printing inks, rubber/plastic processing, pharmaceuticals, lubricants, cosmetics, chemical intermediates and diesel fuel substitute/extender	[2,25,38,39,75,76,203]
Idesia polycarpa var. *vestita* fruit oil	The provinces to the south of Qinling mountain and Huaihe River in China	Tree	Fruit, seed	26.15–26.26	–	2250–3750	–	Oil, biodiesel	[20,38,39]
Jatropha curcas L.	Indonesia, Thailand, Malaysia, Philipines, India, Pakistan, Nepal	Tree	Seed, kernel	20–60	40–60	1590	1892	Oil-illuminant (burns without soot), lubricant, biodiesel	[4,16,25,35,38,43–46,105,136,189,193]
Linum usitatissimum (linseed)	Distributed to the region extending from the eastern Mediterranean to India, wider cultivation of this crop in Europe and its adapted to wide range in Canada and Argentina	Herbaceous annual	Seed	35–45	–	402	478	Oil for wall paint and floor oil, biodiesel resin, fiber, surface coating applications stains, linoleum.	[2,38,136]
Madhuca indica	India	Tree	Seed, kernel	35–50	50	–	–	Biodiesel	[2,16,25,36,38]
Melia azedarach (syringa=persian liliac)	Distributed to India, southern China and Australia	Shrub/tree	Seed, kernel	10–45	2.8	–	–	Biodiesel	[190]
Michela chaampaca	Eastern Himalayas, Assam, Burma, China, Western Ghats and throughout India.	Tree	Seed	45	–	–	–	Oil, biodiesel	[16,17]
Mesua ferrea	Forest in NorthEast India, Karnataka, Kerala		Seed	35–50	–	–	–	Soaps, lubricants, illumination	[35,36,189]
Nicotiana tabacum (tobacco)	Greece, Turkey, Bulgaria, Macedonia, India, England, Pakistan, Serbia, Brazil, Cuba, Columbia, East Africa, Ecuador, Fiji, Guatemala, Haiti, India, Iran, United States, Tanzania	Herb	Seed, kernel	36–41	17	2825	–	Oil, ethnomedicinal	[2,38,39,83,84,87,204,205]
Pongamia pinnata (karanja)	Native Western Ghats in India, northern Australia, Fiji and in some regions of Eastern Asia.	Tree	Seed, kernel	25–50	30–50	900–9000	–	Oil-illuminant, timber, firewood	[4,16,25,35,36,38,39,190]
Putranjiva roxburghii	Distributed in India	Tree	Seed	41–42	–	–	–	Oil-burning, Kernel yield , seeds yield a fatty, oil used for burning an essential oil	[2,39,92]
Pongamia glabra (koroch seed)	Naturally distributed in tropical and temperate Asia, from India to Japan to Thailand to Malesia to north and north-eastern Australia to some Pacific islands	Tree	Seed	33.6	–	225–2250	–	Oil for diesel generator, firewood	[38,39,191]
Raphanus sativus	Widely grown and consumed throughout the world	Herbaceous annual	Seed	40–45	–	–	–		[27,39]
Ricinus communis (castor)	Cuba, Brazil, China, India Italia, French and the countries of the former Sovien Union	Tree/shrub	Seed	45–50	–	1188	1413	Seed oil-fuel, Seeds yield castor oil, a fatty oil used as cathartic and also for lubrication and illumination	[2,136,206,207]
Simmondsia chinensis (jojoba)	Grows in the Mojave and Sonoran deserts of Mexico, California, and Arizona	Shrub	Seed	45–55	–	1528	1818		[2,4,38,39,189,208]
Salvadora oleoides (pilu)	Native in arid regions of Punjab and West India	Tree	Seed	45	–	–	–	Seed is used candle making and candles	[2,35,36,39]
Sapium sebifeum L. *Roxb* (stillingia)	Native in China, Japan, India and grows well in the southern coastal United States	Tree	Seed, kernel	13–32	53–64	–	–	Fatty oil known as strillengia oil, drying oil	[2,15,70]
Sleichera triguga (kusum)	Distributed in the Himalayas, the western Deccan to Sri Lanka and Indo-China. It was probably introduced to Malesia and has naturalized in Indonesia (Java, the Lesser Sunda Islands (Bali and Nusa Tenggara), Sulawesi, the Moluccas, Ceram and the Kai Islands). It is occasionally cultivated throughout the tropics, especially in India	Tree	Seed	–	55–70	–	–	Fuel: the wood is suitable as firewood and makes excellent charcoal. Lipids: Oil extracted from the seed, called 'kusum oil', is a valuable component of true Macassar oil used in hairdressing, used for culinary and lighting purpose, used in traditional medicine to cure itching, acne and other skin afflictions.	[2,11,189,209,210]

Table 1 (*continued*)

Non-edible vegetable source	Distribution	Plant type	Plant part	Oil content		Yields of various plant oils		Uses	Refs.
				Seed (wt%)	Kernel (wt%)	kg oil/ha	liters oil/ha		
Samadera indica	Indonesia, tropical region	Tree	Seed	≈ 35	–	–	–	Oil	[39,189,193]
Sapindus mukorossi (soapnut)	Asia (India, Nepal, Bangladesh, Pakistan), America, Europe	Tree	Seed, kernel	51.8	–	–	–	Oil, biodiesel	[89]
Tomato seed	Turkey, Greece and growing in tropical and semitropical regions	Tree	Seed	32–37	–	5500	–	Oil, manufacture of soaps, pressed cake is used as fodder for cattle and fertilizer	[2,211,212]
Tung	Southwest China	Tree	Seed	35–40	–	790	940	Oil, biodiesel	[22,71,136,208]
Terminala catappa	Brazil	Tree	Seed	49	–	200–500	–	Timber, oil, biodiesel	[25,27,38,39,190]
Ximenia americana	Widespread throughout the tropics: Africa, India and South East Asia to Australia, New Zealand, Pacific Islands, West Indies, Central and South America	Tree	Kernel	–	49–61	–	–	Oil, lubricant	[16,39,191,213–216]

from 15 to 40 m. It can grow between the altitudes of 1200 m and 2450 m respectively [24]. *Croton megalocarpus* is a tree indigenous to East Africa and the seeds have oil content 40–45% oil [52]. A tree of *Croton megalocarpus* produces up to 50 kg of seeds and a hectare produces 5–10 t of seeds per year [24].

2.4. *Moringa oleifera*

Moringa oleifera is a member of the Moringaceae family, grows throughout most of the tropics, it is drought-tolerant and can survive in harsh, poor and infertile land. *Moringa oleifera* is indigenous to northwest India, Africa, Arabia, Southeast Asia and South America. However, it had distributed in the Philippines, Cambodia and Central and North America nowadays. *Moringa oleifera* oil is containing high in oleic acid which is around 70% of the total fatty acid profile [53]. The plant starts bearing Pods 6–8 months after planting and reaches an average of 3 t of seed per hectare per year. The seed contains on average 40% oil by weight [24].

2.5. *Aleurites moluccana*

Aleurites moluccana is another member of the Euphorbiaceae family. It is generically known as the candle nut tree and Hawaiian tree. It thrives in wet or dry subtropical and tropical forest zones. *Aleurites moluccana* grows optimally between the altitudes of 0 and 1200 m; a temperature of 18–28 °C, a rainfall of 650–4300 mm and a soil pH of 5–8. The tree produces spherical fruits, 5 cm or more in diameter, with a thick, rough, and hard nut shell making up to 64–68% of fruit, and the nut shell is difficult to separate from its oil-rich kernel. In plantations, nut yields are estimated at 5–20 $t ha^{-1} yr^{-1}$, each tree producing 30–80 kg of nuts. Oil production varies from 15% to 20% of nut weight. The oil is rich in polyunsaturated oils: linolenic, oleic and various linoleic acids [24].

2.6. *Pachira glabra*

Pachira glabra belongs to the Malvaceae family, in the Bombacaceae subfamily. It is also known as French peanut, Guinea peanut or money. The tree is originally a Brazilian native tree, now grown throughout the tropics and subtropics. It produces green fruits which upon reaching maturity, split open releasing seeds. Trees begin to fruit at about 4–5 years, producing fruits containing 10–25 rounded seeds of average 2.5 cm diameter, with 40–50% oil content [24].

2.7. *Ricinus communis* (Castor)

Ricinus communis belongs to the Eurphorbiaceae family and also called castor beans. It is non-edible oilseed crop that is easily grown and resistant to drought [35,51]. The tree is grown in many countries such as United States, India, China, Central Africa, Brazil and Australia with different cultivation cultures [25,26,35,54]. Its oil is viscous, slightly odor, pale yellow, non-volatile and non-drying oil with a bland taste and is sometimes used as a purgative. On the average, the seeds contain about 46–55% oil [54].

2.8. *Calophyllum inophyllum* L. (Polanga)

Calophyllum inophyllum L. commonly known as polanga or honne, is a non-edible oilseed belongs to the Clusiaceae family. It is a large and medium sized, evergreen sub-maritime tree which grows best in deep soil or on exposed sea sands. The rainfall requirement is 750–5000 mm/yr. This plant has multiple origins including East Africa, India, South-East Asia and Australia [8,16,25,26,55]. The tree supports a dense canopy of glossy,

Fig. 1. Natural tree borne non-edible vegetable oils feedstock for biodiesel [26,89,136,190,208,240–243].

elliptical, shiny and tough leaves, fragrant white flowers, and large round nuts. Its size typically ranges between 8 and 20 m (25–65 ft) tall at maturity, sometimes reaching up to 35 m (115 ft). The growth rate of the tree is 1 m (3.3 ft) in height per year on good sites. Its leaves are heavy and glossy, 10–20 cm (4–8 in.) long and 6–9 cm (2.4–3.6 in.) wide, light green when young and dark green when older. Fruits are spherical drupes and arranged in clusters. The fruit is at first pinkish-green later turning bright green and when ripe, it turns dark gray-brown and wrinkled. The tree yields 100–200 fruits/kg. In each fruit, one large brown seed 2–4 cm (0.8–1.6 in.) in diameter is found. The single, large seed is surrounded by a shell (endocarp) and a thin, 3–5 mm layer of pulp. Oil yield per unit land area has been reported at 2000 kg/ha. The oil is tinted green, thick, and woodsy or nutty smelling [8,26,55–60]. The seed oil has very high oil content (65–75%) [2,55].

2.9. *Sterculia feotida* L.

Sterculia feotida L. plant belongs to sterculiaceae family with 2000 type of species and classified as non-drying oils. It is a wild plant and well adapted to tropical and subtropical area (30°North Latitude–35°South Latitude), although more humid environmental conditions are shown to result in a better crop performance. The plant has an average life span of more than 100 years [61–63]. *Sterculia feotida* L. is a large, straight, deciduous tree growing up to 40 m in height and 3 m in girth, with the branches arranged in whorls and spreading horizontally [64,65], the diameter of trees is 100–120 cm [61,63,66,67]. The ideal planting pitch has been found to be $3 \times 3\ m^2$. The fruit is large, woody, red, nearly smooth and about 10 cm long. It contains from 10 to 15 seeds each, which are black and about 2 cm long. *Sterculia feotida* L. gives a yield of about 200–350 kg/tree/yr of seed and the kernel seeds oil content of 50–60% [23].

2.10. *Madhuca indica*

M*adhuca indica* is mainly found in India [1,7,68,69]. It belongs to the Sapotaceae family and grows quickly to approximately 20 m in height, possesses evergreen or semi-evergreen foliage, and is adapted to arid environments [25,26]. *Madhuca indica* is one of the forest based tree-borne non-edible oils with large production potential of about 60 million tons per annum in India. The *Madhuca indica* tree starts producing seeds after 10 years and continues up to 60 years. The kernel constitutes about 70% of the seed and contains 50% oil [7,26,41]. Each tree yields about 20–40 kg of seed per year depending upon the maturity and size of the tree and the total oil yield per ha is 2.7 t per year. Its seed contains about 35–40% of *Madhuca indica* [68].

2.11. *Sapium sebiferum (Linn.) Roxb (Chinese tallow)*

Sapium sebiferum (Linn.) *Roxb* (Chinese tallow tree) is also commonly referred to as Stillingia tree. It belongs to the Euphorbiaceae family. The tree grows rapidly and can reach maturity within approximately 3–4 years. It can generate economic yields in its productive life span of which ranges between 70 and 100 years. The tree can be grown on marginal land is adapted to alkaline, saline, droughty, and acidic soils. The tree is native to eastern Asia (China, Japan and India) and grows well in the southern coastal United States to prevent soil erosion. The tree produces 4–10 t of seed every year [2,15,51,70]. The seeds contain 45–60% oil. Historically, the tree has been used in soap and candles making, herbal medicine and to prevent soil erosion. Currently, It has been considered useful in the production of biodiesel because it is the third most productive vegetable oil producing crop in the world, after algae and oil palm [51].

2.12. Aleutites fordii (Tung)

Aleutites fordii tree is spread widely in western China, Argentina, Paraguay, Africa, India and United States [71]. It is also commonly referred to as Tung tree. The tree usually bears fruit within 2–4 years and reaches maximum productivity at around 10–12 years of age. The productivity of Tung oil mainly varies from 300 to 450 kg/ha. The oil content of fruit is between 14–20%, the kernel 53–60% and the seed 30–40%. Tung oil has been used in different industrial applications such as ceramic, paint, paper and cloth production. However, recently Tung oil (*Aleutites fordii*) has been regarded as a promising non-edible source of biodiesel production [22,71].

2.13. Azadirachta indica (Neem)

Azadirachta indica (Neem) tree belongs to the Meliaceae family. It is a multipurpose and an evergreen tree, 12–18 m tall, which can grow in almost all kinds of soil including clay, saline, alkaline, dry, stony, shallow soils and even on solid having high calcareous soil. It is native to India, Pakistan, Sri Lanka, Burma, Malaya, Indonesia, Japan, and the tropical regions of Australia. It thrives well in arid and semi-arid climate with maximum shade temperature as high as 49 °C and the rainfall is as low as 250 mm. It can be raised by directly sowing its seed or by transplanting nursery-raised seedlings in monsoon rains. It reaches maximum productivity after 15 years and has a life span of 150–200 years. Planting is usually done at a density of 400 plants per hectare. The productivity of Neem oil mainly varies from 2 to 4 t/ha/yr and a mature Neem tree produces 30–50 kg fruit. The seed of the fruit contains 20–30 wt% oil and kernels contain 40–50% of an acrid green to brown colored oil [2,16,25,26,51,72].

2.14. Hevea brasiliensis (Rubber seed)

Hevea brasiliensis tree, commonly referred to Rubber tree, belongs to the family Euphorbiaceae. This rubber tree originates from the Amazon rain forest (Brazil). The tree is the primary source of natural rubber and produces 99% of world's natural rubber. Moreover, the tree's sap-like extract (known as latex) can be collected and used in various applications. It is distributed mainly in Indonesia, Malaysia, Liberia, India, Sri lanka, Sarawak, and Thailand. Growing up to 34 m in height, the tree requires heavy rainfall and produces seeds weighing from 2 to 4 g that do not currently have any major industrial applications [1,25,26,73]. On an average, a healthy tree can give about 500 g of useful seeds during a normal year and this works out to an estimated availability of 150 kg of seeds per hectare. The seed contains an oily endosperm. Generally 37% by weight of the seed is shell and the rest is kernel. Rubber seed oil is a non-edible vegetable oil, which contain 50–60 wt% oil and kernel contain 40–50 wt% of brown color oil. The oil is high in unsaturated constituents such as linoleic (39.6 wt%), oleic (24.6 wt%), and linolenic (16.3 wt%) acids. Other fatty acids found in rubber seed oil include saturated species such as palmitic (10.2 wt%) and stearic (8.7 wt%) acids [1,2,26,73–78].

2.15. Rice bran

Rice bran is the cuticle between the paddy husk and the rice grain and is obtained as a by-product in the production of refined white rice from brown rice and is common in countries such as China and India [79]. The bran is highly nutritious due to the presence of lipids, protein, minerals and vitamins. It is extracted from white rice bran by which the composition of rice bran varies with the rice type, climatic conditions and rice processing methods [80,81]. The oil content in rice bran varies from 12% to 25% [41,51,81]. The high FFA content of rice bran oil makes it unsuitable for eating purposes. The estimated potential yield of crude rice bran oil is about 8 million metric tons if all rice bran produced in the world were to be harnessed for oil extraction. Rice bran oil is an underutilized non-edible vegetable oil, which is available in large quantities in rice cultivating countries, and very little research has been done to utilize this oil as a replacement for mineral diesel [7,41,82].

2.16. Nicotiana tabacum (Tobacco)

Nicotiana tabacum, commonly referred to tobacco, is a by-product that contains significant amount of oil (35–49% by weight) with an estimated annual yield of 15,000 t per year. It can be cultivated in more than 100 countries worldwide such as Macedonia, Turkey, South Serbia and widespread in North and South America etc. The tree is commonly grown for the collection of leaves [27,83,84]. The oil extracted from tobacco seed is non-edible with physical, chemical and thermal properties that compare favorably with other vegetable oils and have the potentiality to be considered as a new feedstock for biodiesel production [83–87].

2.17. Crambe abyssinica (Hochst)

Crambe abyssinica (hochst or crambe) is an oil plant belongs to cruciferous family. It is native of the Mediterranean region, from Ethiopia to Tanzania. Being its origin the Mediterranean zone and the high lands of the East of Africa, it adapts very well to the cold weather of the wide extensions of Europe. The tree can reach up to 1–2 m height depending on the season and plant density. The flowers are white or yellow. The seeds are held into little capsules and each capsule only contains one greenish brown spherical seed of 0.8–2.6 mm diameter. The capsules generally stay around the seeds after harvest the hull has a volume of 25–30%. The weight of 1000 seeds is approximately 6–10 g. Their seeds contain 35.6–42.8% of oil [88]. The oil can be used as a source to produce biodiesel. However, Very little research has been done to produce biodiesel from this oil.

2.18. Thevettia peruviana (yellow oleander)

Thevettia peruviana is an evergreen perennial shrub native in tropical America, especially Mexico, Brazil and West Indies, and has naturalized in tropical regions of the globe. The tree belongs to Apocynaceae family and is commonly known by various names such as yellow oleander (nerium), gum bush, bush milk, exile tree in India, cabalonga in Puerto Rico, ahanain Guyana, olomi ojo by Yorubas in Nigeria. Its height can reach up to 4.5–6 m with deep green linear sword-shaped leaves and funnel shaped (yellow, white or pinkish yellow colored) flowers. Thevettia plants produce annually more than 400–800 fruits depending on the rainfall and plant age. The plant has annual seed yield of 52.5 t/ha and about 1750 L of oil can be obtained from a hectare of waste land. It has high oil content which is around 67% in its kernel [26].

2.19. Sapindus mukorossi (Soapnut)

Sapindus mukorossi (Soapnut) is generally found in tropical and subtropical climate areas and various parts of the world including Asia (the outer Himalaya of Uttar, Pradesh, Uttaranchal, Himachal Pradesh, Jammu, Kashmir), America and Europe. The plant grows very well in deep loamy soils and leached soils. Therefore, cultivation of soapnut in such soil avoids potential soil erosion. The seed is enclosed in a black, smooth and hard globose endocarp. Soapnut seeds contain 23% oil of which 92% is triglycerides.

The oil from soapnut has been considered as promising non-edible oil having significant potential for biodiesel production. This is because it is the third most productive vegetable oil producing crop in the world, after algae and oil palm [42,89].

2.20. Cerbera odollam (Sea mango)

Cerbera odollam (Sea mango) also sometimes called *Cerbera manghas* L., is a tree belonging to the poisonous Apocynaceae family [90]. *Cerbera odollam* grows well in coastal salt swamps and creeks in south India and along riverbanks in southern and central Vietnam, Cambodia, Sri Lanka, Myanmar, Madagascar and Malaysia [10,26,90]. The *Cerbera odollam* tree grows to a height of 6–15 m and has dark green fleshy lanceolate leaves. The large white flowers have a delicate perfume, reminiscent of jasmine. The fruit, when still green, looks like a small mango, with a green fibrous shell enclosing an ovoid kernel measuring approximately 2 cm × 1.5 cm and consisting of two cross-matching white fleshy halves. On exposure to air, the white kernel turns violet, then dark gray, and ultimately brown or black [26,90]. The oil content from *Cerbera odollam* seeds is 54%. The fatty acid composition of cerbera odollam oil is mainly oleic (48.1%), followed by palmitic (30.3%), linoleic (17.8%) and stearic (3.8%) [10,26].

2.21. Other feedstocks

Euphorbia lathyris L. which belongs to the Euphorbiaceae family can thrive in drought, frost and arid soils. This plant is native to southern Europe, north-western Africa, southwest Asia and western China. The yield of EL seed ranges from 1.5 to 2.5 t/ha/yr, and the oil contents is 48 wt% [70].

Idesia polycarpa var. *vestita*, a tall tree of about 15 m high, is mainly distributed in the provinces to the south of Qinling Mountain and Huaihe River in China. It's a red ripe fruit consists of yellow pulp and dark greenish yellow seed. The oil contents in pulp and seed are about 26.15% and 26.26% (% dry basis) respectively. The yields of oil are 1.5–2.5 kg/tree and 2.25–3.75 t/ha, respectively. *Idesia polycarpa* has great potential of using as a feedstock for biodiesel production [20].

Guizotia abyssinica (GA) belongs to the Compositae family. It is an annual herbaceous plant cultivated in Ethiopia and India in rotation with cereals and pulses. The plant grows to a height of 0.5–1.5 m and reaches the maturity within 110–120 days. The crop is widely adapted to all types of soil and is commonly grown in India on poor and acidic soils or on hilly slopes that are low in fertility. It requires moderate rainfall and grows in temperate and tropical areas. Yield is reported to be 200–300 kg/ha, although they can reach 500–600 kg/ha with good management. The seeds are shinning black in appearance and are very light in weight as 1000 seeds weigh 3–5 g. The seed contains about 30% oil with 25% oleic and 55% linoleic acid in fatty acid composition [91].

Argemone mexicana L. (Common name: Mexican prickly poppy) belongs to the Papaveraceae family. It is a species of poppy found in Mexico and now widely naturalized in the United States, India and Ethiopia. It has been used by the Natives of the western US and parts of Mexico. The plant prefers light (sandy) soils, requires well-drained soil and can grow in nutritionally poor soil. The seeds contain 22–36% of a pale yellow non-edible oil, called argemone oil or katkar oil, which contains toxic alkaloids the sanguinarine and dihydrosanguinarine. The main fatty acids present in *Argemone mexicana* L. seed oil are myristic acid, palmitic acid, stearic acid, oleic acid, linoleic acid and arachidic acid. The non-edible oil from this tree has been found most suitable for biodiesel purpose. [26].

Putranjiva roxburghii (Lucky bean tree) tree belongs to the family Euphorbiacae of order Geranials, which was identified by Roxburgh and accordingly the plant is called as *P. roxburghii*. The tree can reach to a height up to 18 m and a girth of 2 m. Putranjiva oil is yellow in color, highly pungent, volatile and rich in oleic acid. The seeds contain 41–42% of oil [26,92,93].

M. azedarach (syringe) tree belongs to the family Meliaceae. It is a deciduous tree that grows between 7 and 12 m in height. It is native to India, southern China, and Australia. The oil content of dried syringe berries is around 10 wt% [26].

Simarouba glauca tree belongs to the family Simaroubaceae and is commonly known as paradise tree. The tree is native to Florida in the United States, southern Florida and South America. It is a multipurpose tree capable of growing on the degraded soils and can be adapted to a wide range of temperatures (10–45 °C) and altitudes up to 1000 m above sea level. Its seeds contain 50–65% oil that can be extracted by conventional methods [68].

Simmondsia chinensis (Jojoba) tree belongs to the family Simmondsiaceae. It is a perennial shrub that is native to the Mojave and Sonoran deserts of Mexico, California, and Arizona. Jojoba is unique in that the lipid content of the seeds, vary between 45% and 55% of yields, is in the form of long-chain esters of fatty acids and alcohols (wax esters) [26].

Cuphea, of the family Lythraceae, is a large genus of over 200 species of herbs and shrubs growing in the tropics and subtropics of the Americas. *Cuphea* PSR23 is a hybrid between *Cuphea viscosissima* (a species native to the United States) and *Cuphea lanceolata* (a species native to Mexico). The seeds contain up to 35% oil [25,94–97].

Michelia champaca belongs to Magnoliaceae plant family, which is found in Eastern Himalayas, Assam, Burma, China, Western Ghats and throughout India. It is a tall handsome evergreen tree with straight stem and smooth brown bark. Its seeds yielded 45% of oil [17].

Garcinia indica belongs to Guttiferae plant family, which is found in the tropical rain forests of Western Ghats, Konkana, North Kanara, South Kanara, Bombay, Goa and Coorg. *Garcinia indica* seeds yielded 45.5% of oil [17].

Eruca sativa L. is widespread in South Asia and it is known as taramira. It can be considered as a non-edible biodiesel feedstock. *Eruca sativa* L. has a yield of 1106 kg oil/ha and the oil yield is 30% [98].

Hibiscus sabdariffa L. (Roselle) tree belongs to the family Malvaceae. It is also known worldwide by many different common names such as jamaica sorrel, and, in Thai, as krachiap daeng. It is widely cultivated in tropical regions including the northern, south-eastern, central parts of Thailand and China. The seeds contain 18% oil [99].

3. Advantages of non-edible oils

Preliminary evaluation of several non-edible oilseed crops for their growth, feedstock and adaptability show that these feedstocks have the following advantages [2,6,36]:

(1) The adaptability of cultivating non-edible oil feedstocks in marginal land and non-agricultural areas with low fertility and moisture demand.
(2) They can be grown in arid zones (20 cm rainfall) as well as in higher rainfall zones and even on land with their soil cover. Moreover, they can be propagated through seed or cuttings.
(3) They have huge potential to restore degraded lands, create rural employment generation and fixing of up to 10 t/ha/yr CO_2 emissions.

(4) They do not compete with existing agricultural resources.
(5) They eliminate competition for food and feed. Non-edible oils are not suitable for human food due to the presence of some toxic components in the oils.
(6) They are more efficient and more environmentally friendly than the first generation feedstocks. Conversion of non-edible oil into biodiesel is comparable to conversion of edible oils in terms of production and quality.
(7) Less farmland is required and a mixture of crops can be used. Non-edible oil crops can be grown in poor and wastelands that are not suitable for food crops.
(8) Non-edible feedstock can produce useful by-products during the conversion process, which can be used in other chemical processes or burned for heat and power generation. For instance, the seed cakes after oil expelling can be used as fertilizers for soil enrichment.
(9) Most of non-edible oils are highly pest and disease resistant.
(10) The main advantages of non-edible oil are their liquid nature portability, ready availability, renewability, higher heat content, lower sulfur content, lower aromatic content and biodegradability.

4. Problems in exploitation of non-edible oils

Development of non-edible oilseed as alternative biodiesel feedstock in the transportation sector is critical towards achieving higher self-reliance energy security. This situation offers a challenge as well as an opportunity to look for replacement of fossil fuels for both economic and environmental benefits. Under the existing situation of non-edible oils being of forest origin, the problems encountered are [36]:

(1) Collection from scattered locations, high dormancy and problems in picking and harvesting in avenue and forest plantations.
(2) Non-availability of quality planting material or seed, limited period of availability, unreliable and improper marketing channels.
(3) Lack of post-harvest technologies and their processing, non-remunerative prices, wide gap between potential and actual production, absence of state incentives promoting biodiesel as fuel, and economics and cost–benefit ratio.

Table 2 shows the Agro-climatic preferences of some promising non-edible oils.

5. Oil extraction techniques

There are three main methods that have been identified for the extraction of the oil: (i) mechanical extraction, (ii) solvent extraction and (iii) enzymatic extraction. Mechanical pressing and solvent extraction are the most commonly used methods for commercial oil extraction. Before the oil extraction takes place, seeds have to be dried. Seed can be either dried in the oven (105 °C) or sun dried (3 weeks). Mechanical expellers or presses can be fed with either whole seeds or kernels or a mix of both, but common practice is to use whole seeds. However, for chemical extraction only kernels are used as feed [46,100–102].

5.1. Mechanical extraction

The technique of oil extraction using mechanical presses is the most conventional practice. In this type, either a manual ram press or an engine driven screw press can be used. It has been found that, engine driven screw press can extract 68–80% of the available oil while the ram presses only achieved 60–65% (Table 3). This broader range is due to the fact that seeds can be subjected to a different number of extractions through the expeller [46,101,102].

Devan and Mahalaksmi [23,103] used one mechanical expeller to extract the oil from *Sterculia feotida* L (Poon) seeds. Yang et al. [20] indicated that mechanical expeller can be used to extract oil from *Idesia polycarpa* with high yield. Oil from dried and peeled *Calophyllum inophyllum* seed can be extracted either by hydraulic manual machine or screw extruder [104]. Sudrajat [105] extracted the crude *Jatropha* oil (CJO) using mechanical expeller. Foidl et al. [106] used screw press to extract the oil from *Jatropha* seeds.

However, it must be noted that oil extracted by mechanical presses needs further treatment of filtering process and degumming. Another problem associated with conventional mechanical presses is that the design of mechanical extractor is suited for some particular seeds, Therefore the yield is affected if that mechanical extractor is used for other seeds. It has been found that, pretreatment of the seeds, such as cooking can increase the oil yield of screw pressing up to 89% after single pass and 91% after dual pass [46,101,102]. Mahanta and Shrivastava [101] indicated that one of the problems associated with non-edible seeds is that the mechanical presses are not efficient for extraction of oils. Same mechanical press cannot be used for different type of seeds. Therefore, several other methods have been proposed recently such as solvent extraction technique.

5.2. Solvent extraction (chemical extraction)

Solvent extraction is the technique of removing one constituent from a solid by means of a liquid solvent. It is also called leaching. There are many factors influencing the rate of extraction

Table 3
Calculated oil yields (% of contained oil) of mechanical extraction methods [46,100,130,217,218].

Press	Oil yield (%)	Necessary treatment
Engine driven screw press	68.0	Filterization and degumming
	80.0	
	79.0	
Ram press	62.5	
	62.5	

Table 2
Agro-climatic preferences of some promising tree-borne oil seeds [36].

Non-edible vegetable source	Rainfall (mm)	Temperature (°C)	Soil preference	Tree height (m)	Suitability for agro-forestry
Jatropha curcas L.	480–2400	20–28	Any type	3–5	Fence, Alley, Sole
Pongamia	500–2500	Jan–38	Wide range	8–10	Bunds Border
Neem	750–1000	15–45	Deep clay	20	Border, Sole
Mahua	550–1500	Feb–46	Deep clay	18–20	Border, Wastelands
Calophyllum	750–5000	Jul–48	Sand/Loamy	10–25	Wastelands, Sea coast
Simarouba	1000–4000	25–45	Well drained	15	Bunds, Sole

such as particle size, the type of liquid chosen, temperature and agitation of the solvent. The small particle size is preferable as it allows for a greater interfacial area between the solid and liquid. The liquid chosen should be a good selective solvent and its viscosity should be sufficiently low to circulate freely. Temperature also affects the extraction rate. The solubility of the material will increase with the increasing temperature. Agitation of the solvent also affects, it increases the eddy diffusion and therefore increases the transfer of material from the surface of the particles. Solvent extraction is only economical at a large-scale production of more than 50 t biodiesel per day. There are three methods that are used in this type as follow [46,101,102]:

(1) Hot water extraction
(2) Soxhlet extraction
(3) Ultrasonication technique

Mahanta and Shrivastava [101] and Achten et al. [46] indicated that solvent extraction with n-hexane can be used to extract the oil from Jatropha seed and *Pmgamia pinnata*. It is reported that this method could produce about 41% and 95–99% of oil yield respectively. Moreover, several other studies conducted by Kansedo et al. [10], Moser and Vaughn [31], Rashid et al. [53] and Sarin et al. [18] extracted the oil from *Cerbera odollam* (Sea mango), *Coriander (Coriandrum sativum* L.), *Moringa oleifera* and *Guizotia abyssinica* L. using Soxhlet extractor with n-hexane as the solvent.

5.3. Enzymatic oil extraction

Enzymatic oil extraction technique has emerged as a promising technique for extraction of oil. In this process suitable enzymes are used to extract oil from crushed seeds. Its main advantages are that it is environment friendly and does not produce volatile organic compounds. However, the long process time is the main disadvantage associated with this technique [101]. Shah et al. [107] used combination of ultrasonication and aqueous enzymatic method to extract oil from *Jatropha curcus* seed kernels.

Table 4 shows the reaction temperature, reaction pH, time consumption and oil yield of different chemical and enzymatic extraction methods tested on *Jatropha curcas*. It has been found that the chemical extraction using n-hexane method results in the highest oil yield which makes it the most common type. However, this type consumes much more time compared to other types. Furthermore n-hexane solvent extraction has a negative environmental impacts as a result of the wastewater generation, higher specific energy consumption and higher emissions of volatile organic compounds and human health impacts (working with hazardous and inflammable chemicals). Using aqueous enzymatic oil extractions greatly reduces these problems. In aqueous enzymatic oil extraction the use of alkaline protease gave better results. Furthermore, ultrasonication pretreatment is a more useful step in aqueous oil extraction [46,101,102].

6. Fatty acid composition profile of various non-edible oils

Fatty acid composition is an important property for any biodiesel feedstock as it determines the efficiency process to produce biodiesel. The percentage and type of fatty acids composition relies mainly on the plant species and their growth conditions. The fatty acid composition and distribution of some non-edible oils are generally aliphatic compounds with a carboxyl group at the end of a straight-chain. The most common fatty acids are C_{16} and C_{18} acids. However, some feedstocks contain significant amounts of fatty acids other than the typical C_{16} and C_{18} acids [108]. Table 5 shows the chemical structures of common fatty acids of non-edible oils. Table 6 shows the fatty acid composition of various non-edible oils that were found suitable for production of biodiesel. Moreover, more fatty acid compositions can also be found in Refs. [4,16,25,27,78] for further reading.

7. Technologies of biodiesel production from non-edible oils

It is well known that viscosity is the main barrier that prevents the use of direct vegetable oils in conventional diesel engines [1,4]. Therefore, there are many techniques, methods and processes that have been used recently to produce biodiesel from various non-edible feedstocks. These methods include [1,3,4,69, 101,109–114]; pyrolysis, micro emulsification, dilution, and transesterification. The flowchart shown in Fig. 2 describes the route to produce biodiesel from non-edible oil seeds [115]. The following section will give a brief summary of these technologies.

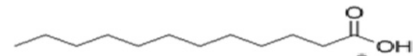
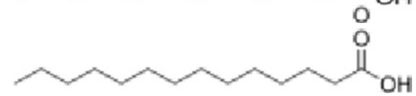
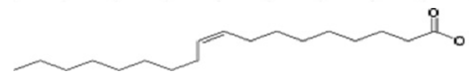
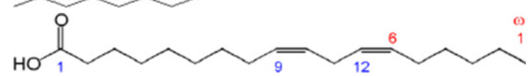
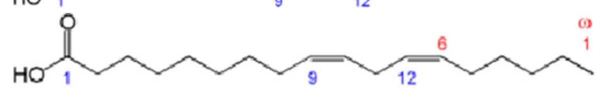
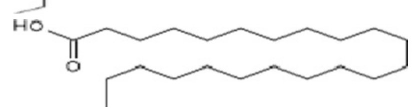
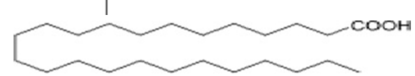
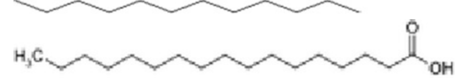
7.1. Pyrolysis (Thermal cracking)

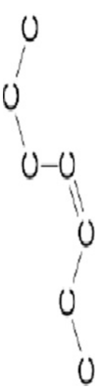
Pyrolysis is the thermal conversion of the organic matters in the absence of oxygen and in presence of a catalyst. The paralyzed material can be vegetable oils, animal fats, natural fatty acids or methyl esters of fatty acids. Thermal decomposition of triglycerides produces alkanes, alkenes, alkadines, aromatics and carboxylic acids. The liquid fractions of the thermally decomposed vegetable oils are likely to approach diesel fuels. The pyrolyzate had lower viscosity, flash point, and pour point than diesel fuel and equivalent calorific values. However, cetane number of the

Table 4
Reported oil yields percentage for different chemical and enzymatic extraction methods and different reaction parameters [46].

Extraction method	Reaction temperature (°C)	Reaction pH	Time consumption (h)	Oil yield (%)
n-hexane oil extraction (Soxhelt) apparatus	–	–	24	95–99
1st acetone 2nd n-hexane	–	–	48	
Aqueous oil extraction (AOE)	– 50	– 9	2 6	38 38
AOE with 10 min of ultrasonication as pretreatment	50	9	6	67
Aqueous enzymatic oil extraction (AEOE) (hemicellulase or cellulase)	60	4.5	2	73
AEOE (alkaline protease)	60 50	7 9	2 6	86 64
AEOE (alkaline protease) with 5 min of ultrasonication as pretreatment	50	9	6	74
Three-phase partitioning	25	9	2	97

Table 5
Chemical structures of common fatty acids [4,112,114,219–222].

Name of fatty acid	Chemical name	Chemical Formula	Geometric chemical structure	Number of carbons	Number of double bonds
Lauric aric	Dodecanoic	$CH_3(CH_2)_{10}COOH$		12	0
Myristic	Tetradecanoic	$CH_3(CH_2)_{12}COOH$		14	0
Palmatic	Hexadecanoic	$CH_3(CH_2)_{14}COOH$		16	0
Palmitoleic	Cis-9-hexadecnoic acid	$CH_3(CH_2)_5CH=CH(CH_2)_7COOH$		16	1
Stearic	Octadecanoic	$CH_3(CH_2)_{16}COOH$		18	0
Oleic ciz-9	Octadecanoic	$CH_3(CH_2)_7CH=CH(CH_2)_7COOH$		18	1
Linoleic	Carboxylic acid	$CH_3CH_2CH=CHCH_2CH=CH(CH_2)_7COOH$		18	2
Linolenic	Cis-9, cis-12, cis-15-Octadecatrieoic	$CH_3CH_2CH=CHCH_2CH=CHCH_2CH=CH(CH_2)_7COOH$		18	3
Stearidonic acid	Octadecatetraenoic acid	$C_{18}H_{28}O_2$		18	4
Arachidic	Eicosanoic	$C_{20}H_{40}O2$		20	0
Gondoic acid	Eicosenoic acid	$CH_3(CH_2)_{18}COOH$		20	1
Behenic	Docosanoic	$CH_3(CH_2)_{20}COOH$		22	0
Erucle	cis-13-docosenoic	$CH_3(CH_2)_7CH=CH(CH_2)_{11}COOH$		22	1
Lignoceric	Tetracasanoic	$CH_3(CH_2)_{22}COOH$		24	0
Margaric	Heptadecanoic acid	$CH_3(CH_2)_{15}COOH$		17	0
Capric	Decanoic acid	$CH_3(CH_2)_8COOH$		10	0

Caprylic	Octanoic acid	$C_8H_{16}CO_2$		8	0
Caproic	Hexanoic acid	$C_6H_{12}COOH$		6	0
Saturates	–	–		–	–
Trans unsaturates	–	–		–	–
Cis unsaturated	–	–			

pyrolyzate was lower compared to diesel fuel. The pyrolyzed vegetable oils contain acceptable amounts of sulfur, water content, copper corrosion values and sediments but unacceptable ash, carbon residual and pour point [1,3,4,43,101,111–114,116,117]. The pyrolysis process can be divided into three subclasses which are conventional pyrolysis, fast pyrolysis and flash pyrolysis depending on the operating conditions. Table 7 presents the range of the main operating parameters for pyrolysis processes [101,118–120]. Many investigators have studied the pyrolysis of non-edible vegetable oils and their cakes such as Babassu, Karanja (*Pongamia pinnata*), *Jatropha curcas*, Copra, mahua (*Madhuca indica*), Tung and Castor oil to obtain the suitable alternative and renewable fuel for internal combustion engine. For instance, Tung oil (*Aleutites fordii*) was saponified with lime and then thermally cracked to yield crude oil, which was refined to produce diesel fuel and small amounts of gasoline and kerosene [1,7,114,116,117,121–123].

7.2. Microemulsification

Microemulsification is defined as transparent, equilibrium thermodynamically stable colloidal dispersion of microstructure with diameter ranges from 100 to 1000 Å. Micro emulsion can be made of vegetable oils with an ester and dispersant (co solvent), or of vegetable oils, and alcohol such as ethanol, ethanol, buthanol, hexanol and a surfactant and a cetane improver, with or without diesel fuels. Microemulsification has been considered as a reliable approach to solve the problem of the high viscosity of vegetable oils [1,3,4,7,43,101,111–114,116,117,124].

7.3. Dilution

Non-edible oil can be diluted with diesel to reduce the viscosity and improve the performance of the engine. This method does not require any chemical process [1,7,43,101,116]. It has been reported that substitution of 100% vegetable oil for diesel fuel is not practical. Therefore, blending of 20–25% vegetable oil to diesel has been considered to give good results for diesel engine [3,4,43,116,117]. The use of blends of conventional diesel fuel with a variety of non-edible oils such as Rubber seed, Turpentine, Linseed, *Putranjiva roxburghii*, Cotton seed, *Jatropha curcas* and *Pongamia pinnata* oil has been described in literature [7,75,92,113,125–133].

7.4. Transesterification (Alcoholysis)

Transesterification or alcoholysis is defined as the chemical reaction of alcohol with vegetable oils. In this reaction, methanol and ethanol are the most commonly used alcohols because of their low cost and availability. This reaction has been widely used to reduce the viscosity of vegetable oil and conversion of the triglycerides into ester. The transesterification reaction is shown in Fig. 3. Transesterification can be carried out by two ways: (i) catalytic transesterification and (ii) non-catalytic transesterification [1,3,4,7,43,101,112–114,116,134]. Juan et al. [135] reviewed biodiesel production from Jatropha oil using catalytic and non-catalytic approaches. A summary of several catalytic transesterification methods of some selected non-edible oils is shown in Table 8.

It is widely known that catalytic transesterification is confronted with two problems. The main problem is the processes are relatively time consuming and needs separation of the vegetable oil/alcohol/catalyst/saponified impurities mixture from the biodiesel. Furthermore, the wastewater generated during biodiesel purification is not environment friendly [101]. Under such condition, the supercritical alcohol transesterification is one

Table 6
Fatty acid profiles of various non-edible feedstock.

Non-edible feedstock	C 8:0	C10:0	C12:0	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	C20:0	C20:1	C20:2	C22:0	C22:1	C24:0	C24:1	Refs.
Almondkernel	–	–	–	–	6.5	0.5	1.4	70.7	20.0	–	–	–	–	–	–	–	–	[4]
Andiroba	–	–	–	–	27	1	7	49	16	–	–	–	–	–	–	–	–	[4]
Aphanamixis polystachya (meliaceae)	–	–	–	–	23.1	–	12.8	21.5	29.0	13.6	–	–	–	–	–	–	–	[16,39]
Argemone mexicana	–	–	–	0.8	14.5	–	3.8	18.5	61.4	–	1.0	–	–	–	–	–	–	[16,26,39]
Asclepias syriaca (milkweed)	–	–	–	–	5.9	6.8	2.3	34.8	48.7	1.2	–	–	–	–	–	–	–	[27]
Azadirachta indica (neem)	–	–	–	0.2–0.26	14.9	0.1	20.6	43.9	17.9	0.4	1.6	–	–	0.3	–	0.3	–	[4,51]
Brassica carinata (ethiopian mustard)	–	–	–	–	4–6	–	1.3	10–17	17–25	10–17	0.7	–	–	–	–	–	–	[4,25]
Babasu	0.5	3.8	48.8	17.2	9.7	–	4	14.2	1.8	–	–	–	–	–	–	–	–	[51]
Calophyllum inophyllum L.	–	–	–	0.09	14.6	2.5	19.96	37.57	26.33	0.27	0.94	0.72	–	–	–	2.6	–	[104]
Calophyllum inophyllum L.	–	–	–	–	17.9	2.5	18.5	42.7	13.7	2.1	–	–	–	–	–	2.6	–	[26]
Celastrus paniculatus Linn.	–	–	–	–	25.1	–	6.7	46.1	15.4	3.0	–	–	–	–	–	–	–	[16,39]
Cuphea viscosissima	–	–	–	4.7	18.2	–	3.5	46.9	22.8	2.3	0.6	–	–	0.4	–	0.6	–	[51]
Crambe abyssinica	–	–	–	0	2	–	1	19	–	7	2	–	–	1	59	1	–	[4]
Cumaru	–	–	–	–	23	–	7	37	29	–	–	–	–	–	–	–	–	[4]
Camelina	–	–	–	–	5.0	–	2.2	17.7	18	37.9	1.4	9.8	1.6	0.4	4.5	0.3	0.2	[51]
*Euphorbia lathyris*L.	–	–	–	–	6.8	0.5	1.98	81.46	3.71	2.78	–	0.5	–	–	0.2	–	–	[70]
Guizotia abyssinica L. (niger)	–	–	–	–	9.2	–	9	71.7	–	–	–	–	–	–	–	–	–	[18]
Hevea brasiliensis (rubber)	–	–	–	2.2	10.2	–	8.7	24.6	39.6	16.3	–	–	–	–	–	–	–	[203]
Idesia polycarpa var. *vestita* fruit oil	–	–	–	–	15.6	6.5	1.18	5.5	70.6	1.1	–	–	–	–	–	–	–	[20]
Joannesia princeps Vell	–	–	–	2.4	5.4	–	–	45.8	46.4	–	–	–	–	–	–	–	–	[16,39]
Jatropha curcas L.	–	–	–	1.4	12.7	0.7	5.5	39.1	41.6	0.2	0.2	–	–	–	–	–	–	[4,51,104,105]
Jatropha curcas L.	–	–	–	1.4	15.6	–	9.7	40.8	32.1	–	0.4	–	–	–	–	–	–	[26]
Lesquerella fendleri	–	–	–	0.1	0.9	0.3	1.7	13	5.8	10.6	0.7	–	–	–	–	–	0.4	[51]
Linum usitatissimum (linseed)	–	–	–	–	4.4	0.3	3.8	20.7	15.9	54.6	0.2	–	–	0.3	–	0.1	–	[4,51]
Madhuca indica (mahua)	–	–	–	–	16.0–28.2	–	20.0–25.1	41.0–51.0	8.9–13.7	–	0.0–3.3	–	–	–	–	–	–	[4]
Madhuca indica (mahua)	–	–	–	1.0	17.8	–	14.0	46.3	17.9	–	3.0	–	–	–	–	–	–	[26]
Melia azedarach	–	–	–	0.1	10.1	1.5	3.5	21.8	64.1	0.4	0.2	0.3	–	–	–	–	–	[16,139]
Melia azadirach Linn.	–	–	–	0.1	8.1	1.5	1.2	20.8	67.7	–	–	–	–	–	–	–	–	[26]
Mesua ferrea Linn.	–	–	–	0.9	10.8	–	12.4	60.0	15.0	–	0.9	–	–	–	–	–	–	[16,39]
Michela chaampaca	–	–	–	–	20.7	6.9	2.5	–	–	42.5	–	2.6	–	–	–	–	–	[4]
Nicotiana tabacum (tobacco)	< 0.01	< 0.01	< 0.01	0.09	10.96	0.2	3.34	14.54	69.49	0.69	0.25	0.13	–	0.12	< 0.01	0.04	–	[4,85]
Piqui	–	–	–	–	40	–	2	47	4	–	–	–	–	–	–	–	–	[4]
Putranjiva roxburghii	–	–	–	–	8.0	–	15.0	56.0	18.0	–	3.0		–	–	–	–	–	[4,16]
Putranjiva roxburghii	–	–	–	0.03	10.23	0.07	10.63	48.65	27.5	0.87	1.05	0.3		0.24	0.03	0.31	–	[26]
Pongamia pinnata (karanja)	–	–	–	–	3.7–7.9	–	2.4–8.9	44.5–71.3	10.8–18.3	–	4.1	2.4	–	5.3	–	1.1–3.5	–	[16,25]
Pongamia pinnata Pierre	–	–	–	–	10.6	–	6.8	49.4	19.0	–	4.1	2.4	–	5.3	–	2.4	–	[26]
Rice brand	–	–	–	0.3	12.5	–	2.1	47.5	35.4	1.1	0.6	–	–	0.3	–	0.2	–	[51]
Ricinus communis (castor)	–	–	–	–	1.1	0	3.1	4.9	1.3	0.6	0.7	–	–	–	–		–	[4,139]
Sapium sebifeum Lin. Roxb (stillingia)	–	–	0.4	0.1	7.5	3.71	2.3	16.7	31.5	41.5	–	0.59	–	–	–	–	–	[51,70]
Schleichera triguga	–	–	0.31	15.54	10.35	–	11.11	27.08	6.14	–	15.79	6.17	0.08	0.01	–	–	–	[26]
Sesamum indicum (Sesame)	–	–	–	–	11.0		7.0	43.0	35.0	–	–	–	–	–	–	–	–	[4,139]
Sterculia feotida L.	–	–	–	–	22.4	–	7.3	16.4	45.6	–	6.46	–	–	–	–	–	–	[23]
Thevetia peruviana Merrill	–	–	–	–	15.6	–	10.5	60.9	5.2	7.4	0.3	–	–	0.1	–	–	–	[26]
Thlaspi arense L. (field Pennycress)	–	–	–	0.1	3.1	–	0.5	11.1	22.4	11.8	0.3	8.6	1.6	0.6	32.8	2.9	–	[139]
Tung	–	–	–	–	1.8	–	2.1	5.3	6.8	0.7	0.2	0.1	–		–	10.4	–	[51]
Terminalia catappa	–	–	–	–	35.0	–	5.0	32.0	28.0	–	–	–	–	–	–	–	–	[51,144]
Terminalia belerica Robx.	–	–	–	–	35.0	–	–	24.0	31.0	–	–	–	–		–	–	–	[16,25]
Terminalia chebula Retz	–	–	–	–	19.7	–	2.4	37.3	39.8	–	0.6	–	–	0.2	–	–	–	[4,16]
Ximenia americana Linn.	–	–	–	–	–	–	1.2	60.8	6.7	–	–	–	–	–	–	–	–	[16]
Zanthoxylum bungeanum	–	–	–	–	10.6	5.2	1.4	32.1	25.6	24.1	–	–	–	–	–	–	–	[139]
Ziziphus mauritiana L.	–	–	–	–	10.4	–	5.5	64.4	12.4	–	1.8	2.6	1.2	–	1.7	–	–	[16]

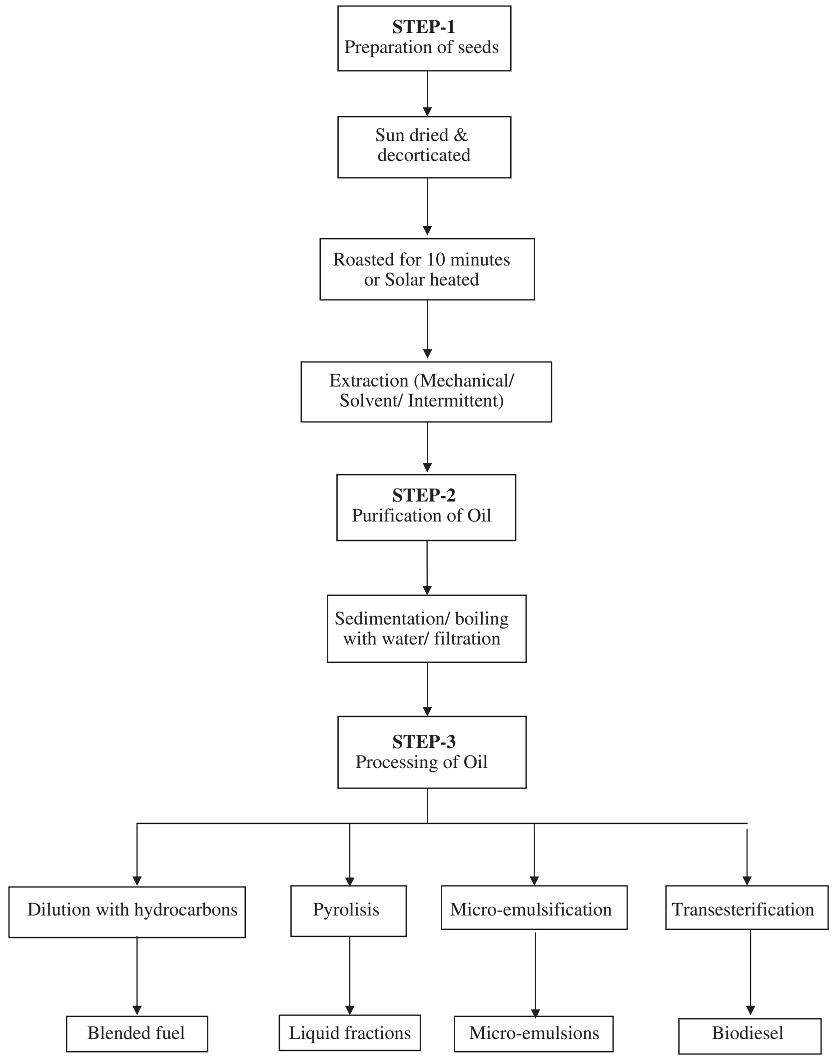


Fig. 2. Process flowchart of non-edible crops seed to biodiesel [115].

Table 7
The range of the main operating parameters for pyrolysis processes [118–120].

Parameter	Conventional pyrolisis	Fast pyrolysis	Flash pyrolysis
Pyrolysis temperature (K)	550–950	850–1250	1050–1300
Heating rate (K/s)	0.1–1	10–200	>1000
Particle size (mm)	5–50	<1	<0.2
Heating time (s)	450–550	0.5–10	<0.5

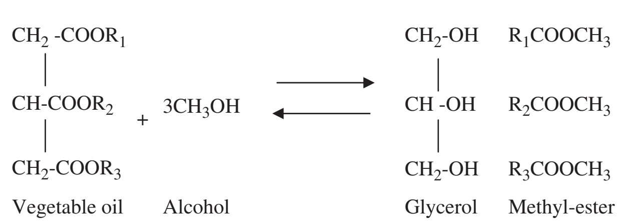


Fig. 3. Transesterificatio reaction of triglycerides [1,3,4,32,43,101,109,112,114,134,156,229,244,245].

option to solve the problems by employing two phased methanol/oil mixtures by forming a single phase as result of the lower value of the dielectric constant of methanol in supercritical state. As a result, the reaction was found to be complete in a very short time [1]. Moreover, purification of biodiesel is much easier as no catalyst is required during supercritical transesterification process, thus preventing soap formation or saponification to occur. However, the drawbacks of supercritical alcohol transesterification process are due to the high temperature and pressure that result in the high cost of the apparatus [43]. Many researchers have been working on non-edible biodiesel production from various feedstocks under different conditions using supercritical alcohol transesterification. Table 9 summarizes some of these studies.

8. Biodiesel standards and characterization

Biodiesel has different physical and chemical properties compared with diesel fuel. The quality of biodiesel fuel can be influenced by various factors include: the quality of feedstock, fatty acid composition of the feedstock, type of production and refining process employed and post production parameters. Therefore, it is required a standard and characteristic of biodiesel fuel. The establishment of standardization for biodiesel has to be wholly owned by many countries. It is utilized to protect both biodiesel consumers and producers as well as to support the development of biodiesel industries. All alternative biodiesel fuels should meet the international standard specification of biodiesel

Table 8
Summary of catalytic transesterification methods of some selected non-edible oils.

Non-edible oil	Catalysts	Catalyst concentration	Alcohol	Molar ratio	Temperature (°C)	Reaction time	Yield FAME	Refs.
Jatropha curcas L.	Pretreatment acid catalayzed (H_2SO_4, KOH, $MeOCH_3$)	0.8%	Methanol	9:1	45	120 min	90–91%	[25]
	One step alkali catalyzed (NaOH)	1.6%		–	70	60 min		
Jatropha curcas L.	KOH	0.55% (w/w)	Methanol	5:1	60	24 min	99%	[27]
Jatropha curcas L.	*Rhyzopus oryzae* (RL)	4% (w/w)	Methanol	3:1	30	60 h	80%	[223]
Jatropha curcas L.	*Pseudomonas cepacia* lipase immobilized	–	Ethanol	–	50	8 h	98%	[224]
Jatropha curcas L.	H_2SO_4	1% (w/w)	Methanol	0.60% (w/w)	50	1 h	90%	[225]
	NaOH	1.4% (w/w)		0.24% (w/w)	65	2 h		
Jatropha curcas L.	H_2SO_4 NaOH	1% (w/w) 1% (w/w)	Methanol	3:10 (v/v) 3:10 (v/v)	65 °C 50	1 h 2 h	21.2% 90.1%	[226]
Jatropha curcas L.	SO_4^{2-}/TiO_2 (ST) KOH	4% (w/w) 1.3%	Methanol	20:1 6:1	90 64	2 h 20 min	> 98%	[227]
Jatropha curcas L.	H_2SO_4 KOH	1.43% (v/v) 0.55% (w/v)	Methanol	0.28 (v/v) 0.16 (v/v)	60 60	88 min 24 min	> 99%	[228]
Madhuca indica	Pretreatment acid catalayzed (H_2SO_4, NaOH)	NaOH 0.7% (w/w)	Methanol	6:1	60	180 min	98%	[25]
Madhuca indica	KOH	0.7% (w/w)	Methanol	6:1	60	30 min	98%	[27]
Calophyllum inophyllum L.	Pretreatment acid catalayzed (H_2SO_4, KOH)	KOH 1.5%	Methanol	6:1	65	4 h	85%	[25]
Rice bran	Two step acid-catalyzed (H_2SO_4)	–	Methanol	10:1	60	–	< 96%	[4]
Rice bran	NaOH	0.75% (w/w)	Methanol	9:1	55	60 min	90.2%	[27]
Pongamia pinnata	NaOH	1–1.5 (w/w)%	Methanol	6:1	65	40–180 min	90.4%	[25]
Pongamia pinnata	KOH	1%	Methanol	6:1	65	180min	97–98%	[27]
Azadirachta indica	NaOH	0.6% (w/w)	Methanol	6:1	65 °C	60 min	83%	[25]
Hevea brasiliensis	NaOH	1% (w/w)	Methanol	6:1	60	60 min	84.46%	[25]
Hevea brasiliensis	H_2SO_4 KOH	1.0% (v/v) 0.5% (w/v)	Methanol	0.75% (v/v) 0.3% (v/v)	63 (± 2) 55(± 5)	1 h 40 min	98–99%	[229]
Brassica carinata (low erucic)	KOH	1.4%	Methanol	4.6:1	45	30 min	91.9%	[25]
Brassica carinata	KOH	1.2% (w/w)	Methanol	6:1	25	60 min	97%	[27]
Camelina sativa	NaOH	1.5% (w/w)	Methanol	6:1	25 °C	60 min	97.4%	[25]
Camelina sativa	KOH	1.5% (w/w)	Methanol	6:1	–	60 min	98%	[27]
Terminala catappa	CH_3CH_2ONa	0.2:1 (molar ratio)	Methanol	6:1	–	–	93%	[25]
Aslepias syiraca	CH_3ONa–KOH	1.1% (w/w)	Methanol	6:1	60	60 min	> 99%	[25]
Cerbera odollam	NaOH Mont morillonite KSF Sulfated zirconia alumina	1% (w/w) 4% (w/w) 5% (w/w)	Methanol	6:1 10:1 8:1	64.7 150 180 °C	60 min 120 min 180 min	8.3% 48.32 83.8%	[10]
Melia azedarach	NaOH	1% (w/w)	Methanol	9:1	36	40 min	63.8%	[27]
Jojoba	KOH	1.35% (w/w)	Methanol	6:1	25	60 min	83.5%	[27]
Raphanus sativus	NaOH	0.6% (w/w)	Ethanol	11.7:1	38	60 min	99.1%	[27]
Stillingia oil	Novozym435, Lipozyme TLIM and Lipozyme RMIM	15% (w/w)	Methanol	1:5	40	10 h	89.5%	[15]
Croton megalocarpus	KOH	1% (w/w)	Methanol	30% (w/w)	60 °C	60 min	88%	[29]
Croton megalocarpus	SiO_2 (SO_4^{2-}/SnO_2–SiO_2)	3% (w/w)	Methanol	15:1	180	2 h	95%	[30]
Moringa oleifera	$NaOCH_3$	1% (w/w)	Methanol	6:1	60	1 h		[53]

such as ASTM 6571, EN 14214, etc. These standards describe the physical and chemical characteristics of variety biodiesel produced from non-edible and edible oil resources. Some of these properties include; caloric value (MJ/kg), cetane number, density (kg/m^3), viscosity (mm^2/s), cloud and pour points (°C), flash point (°C), acid value (mg KOH per g-oil), ash content (%), copper corrosion, carbon residue, water content and sediment, distillation range, sulfur content, glycerin (% m/m), phosphorus (mg/kg), oxidation stability [51,136–138]. Table 10 gives ASTM 6751 and EN 14214 specifications of biodiesel fuels beside ASTM D975 for

Table 9
Supercritical transesterification of non-edible oil with optimized reaction variables.

Non-edible oil	Reactant	Molar ratio	Temperature	Supercritical condition	Reaction time (min)	Alkyl ester yield (%)	Refs.
Pongamia pinnata & *Jatropha curcas* L.	Methanol and ethanol	50:1	300 °C	200 bar	40	80–85	[230]
Linseed oil	Methanol	41:1	503–523 K	–	8–12	88–98	[231]
Jatropha curcas L.	Methanol	43:1	320 °C	8.4 MPa	4	100	[232]
Jatropha curcas L.	Dymetil carbonate	14:1	300 °C	9 MPa	15	> 97	[233]

diesel fuel. Table 11 gives a summary of standard specifications of biodiesel in several countries around the world. Moreover, a summary of some important characteristics of biodiesel are listed in Table 12.

9. Properties and characteristics of non-edible biodiesel

Considerable efforts have been made to develop non-edible oil derivatives that approximate the properties and performance of biodiesel fuels [2]. Criteria for determining properties of non-edible biodiesel are now becoming a relevant subject due to the increase in alternative fuels worldwide. The issue of biodiesel production from alternative non-edible feedstock has been reviewed recently from several different viewpoints [10–12, 15–17, 19,21,22,24,26,28,36,38,41,45,47,48,50,51,68,69,71,74,76,85,88, 89,94,99,114,139–149]. Researchers have shown that the properties of non-edible biodiesel may vary significantly depending on their chemical compositions and fatty acid composition, which give obvious effect on engine performance and emissions. Therefore, when considering a specific non-edible biodiesel a measurement of its properties is required. The physical and chemical properties of various non-edible biodiesel are shown in Table 13. Moreover, more physical and chemical properties of many other non-edible biodiesel can also be found in Refs. [38,51] for further reading.

9.1. Cloud point (CP) and pour point (PP)

The cloud point (CP) and pour point (PP) are important for low-temperatures applications for fuel. The CP is defined as the temperature at which a cloud of wax crystals first appear when the fuel is cooled under controlled conditions during a standard test. The PP is the temperature at which the amount of wax form of a solution is sufficient to gel the fuel. Thus, it is the lowest temperature at which the fuel can flow. In general, biodiesel has higher CP and PP than diesel fuel [1,150]. The CP and PP of non-edible biodiesel varies significantly with feedstock depending on fatty acid compositions. The parameter is specified through the biodiesel ASTM D2500 and D97 respectively [51,138]. Evaluation of cloud points of some non-edible biodiesel feedstocks shows that *Ricinus communis* (castor) methyl ester has the lowest CP of −13.4 °C while *Azadirachta indica* has the highest CP of 14.4 °C. On the other hand, *Thlaspi arense* L. methyl ester has the lowest PP of −18 °C and *Madhuca indica*, *Pongamia glabra*, *Terminalia belerica Robx.* and *Terminalia catappa* methyl ester have the highest PP of 6 °C (Table 13).

9.2. Cold filter plugging point (CFPP)

Cold filter plugging point (CFFP) is as used indicator of low temperature operability of fuels. The Cold filter plugging point (CFPP) refers to the temperature at which the test filter starts to plug due to fuel components that have started to gel or crystallize. CFPP defines the fuels limit of filterability, having a better characteristic than cloud point for biodiesel as well as petrodiesel. Usually, the CFPP of a fuel is lower than its cloud point. The CFFP tested is measured by ASTM D6371 [51]. From Table 13, it has been found that the highest CFFP is found for *Azadirachta indica* (neem) methyl ester with temperature of 11 °C while *Thlaspi arense* L. methyl ester has the lowest temperature of −17 °C.

9.3. Flash point (FP)

Flash point is another important property for biodiesel fuel. Flash point of a fuel is the temperature at which it will ignite when exposed to a flame or a spark. Flash point varies inversely with the fuel's volatility. The flash point is the lowest temperature at which fuel emits enough vapors to ignite. Biodiesel has a high flash point which is usually more than 150 °C, while generally conventional diesel fuel has a flash point of 55–66 °C. Flash point is measured according to ASTM D93 and EN ISO 3679 [51,136,138,150]. From Table 13, it has been found that *Putranjiva roxburghii* methyl ester has the lowest flash point of 48 °C.

9.4. Kinematic viscosity

Viscosity is defined as the resistance of liquid to flow. It refers to the thickness of the oil, and is determined by measuring the amount of time taken for a given measure of oil to pass through an orifice of a specified size [151]. Kinematic viscosity is the most important property of biodiesel since it affects the operation of fuel injection equipment, particularly at low temperatures when an increase in viscosity affects the fluidity of the fuel [1,150]. Moreover, high viscosity may lead to the formation of soot and engine deposits due to insufficient fuel atomization. It has been shown that the viscosity oil methyl esters decrease sharply after transesterification processes of biodiesel. The kinematic viscosity in biodiesel is determined using ASTM D445 (1.9–6.0 $mm^2\ s^{-1}$) and EN ISO 3104 (3.5–5.0 $mm^2\ s^{-1}$) [51,138]. Table 13 shows that *Ricinus communis* methyl ester has the highest kinematic viscosity of 15.25 mm^2/s and *Vernicia fordii* methyl ester lowest marks the kinematic viscosity of 2.5 mm^2/s.

9.5. Cetane number

The CN is a measure of the ignition quality of diesel fuel during combustion ignition [151]. It provides information about the ignition delay (ID) time of a diesel fuel upon injection into the combustion chamber. High CN implies short ignition delay. Fuels with low CN tend to cause diesel knocking and show increased gaseous and particulate exhaust emissions (PM) due to incomplete combustion. Moreover, excessive engine deposits are reported. Cetane number (CN) is based on two compounds which are hexadecane with a CN of 100 and heptamethylnonane with a CN of 15. The CN of biodiesel is generally higher than diesel fuels [1,25,152]. The CN of biodiesel specified by ASTM D613 is 47 min and EN ISO 5165 is 51 min [138]. The CN of variety of biodiesel produced from non-edible oil feedstock is shown in Table 13. From the table, it has been found that *Pongamia glabra* methyl ester has the lowest cetane number of 45.39 while *Rice bran* methyl ester has the highest cetane number of 73.6.

Table 10
ASTM D975, ASTM 6751 and EN 14214 specifications of diesel and biodiesel fuels [1,4,7,134,137,138,234].

Property specification	Unit	Diesel ASTM D975		Biodiesel			
				ASTM D6751		EN 14214	
		Test method	Limits	Limits	Test Method	Limits	Test Method
Flash point	°C	ASTM D975	60 to 80	130 minimum	ASTM D93	101 minimum	EN ISO 3679
Cloud point	°C	ASTM D975	−15 to 5	−3 to −12	ASTM 2500	–	–
Pour point	°C	ASTM D975	−35 to −15	−15 to −16	ASTM 97	–	–
Cold filter plugging point (CFFF)	°C	EN 590	−8	Max +5	ASTM D6371	–	EN 14214
Cetane number		ASTM D4737, EN 590	46	47 minimum	ASTM D613	51 minimum	EN ISO 5165
Density at 15 °C	kg/m3	ASTM D1298	820–860	880	D1298	860–900	EN ISO 3675/12185
Kinematic viscosity at 40 °C	mm2/s	ASTM D445	2.0 to 4.5	1.9–6.0	ASTM D445	3.5–5.0	EN ISO 3104
Iodine number	g I2/100 g	–	–	–	–	120	EN 14111
Acid number	mg KOH/g	–	–	0.5 maximum	ASTM D664	0.5 maximum	EN 14104
Oxidation stability		ASTM D2274	25 mg/L maximum	–	–	3 h minimum	EN 14112
Stoichiometric air/fuel ratio	w/w	–	–	13.8	ASTM PS 121	–	–
Cold soak filtration	s	–	–	360	ASTM D6751	–	–
Carbon residue	% m/m	ASTM D4530	0.2 maximum	0.050 maximum	ASTM D4530	0.3 maximum	EN ISO 10370
Copper corrosion		ASTM D130	Class 1 max	No. 3 maximum	ASTM D130	Class 1	EN ISO 2160
Distillation temperature	°C	ASTM D86	370 maximum	360	ASTM D1160	–	–
Lubricity (HFRR)	m	IP 450	0.460 mm ($_{max}$) (all diesel containing less than 500 ppm sulfur)	520 maximum	ASTM D6079	–	–
Sulphated ash content	%mass	–	–	0.002 maximum	ASTM D874	0.02 maximum	EN ISO 3987
Ash content	%mass	ASTM D482	100 maximum	–	–		
Water and sediment		ASTM D2709	0.05 maximum	0.005 vol% maximum	ASTM D2709	500 mg/kg maximum	EN ISO 12937
Moisture	wt%	–	–	–	–	0.05 maximum	EN 1412
Monoglycerides	%mass	–	–	–	–	0.8 maximum	EN 14105
Diglycerides	%mass	–	–	–	–	0.2 maximum	EN 14105
Triglycerides	%mass	–	–	–	–	0.2 maximum	EN 14106
Free glycerin	%mass	–	–	0.02 maximum	ASTM D6584	0.02 maximum	EN 1405/14016
Total glycerin	%mass	–	–	0.24	ASTM D6548	0.25	EN 14105
Phosphorous	%mass	–	–	0.001 maximum	ASTM D4951	0.001 maximum	EN 14107
Calcium	%mass	–	–	–	–	–	–
Magnesium	%mass	–	–	–	–	–	–
Sulfur (S 10 grade)		ASTM D5453	10 maximum	–	–	–	–
Sulfur (S 15 grade)	ppm	–	–	150 maximum	ASTM D5453	–	–
Sulfur (S 50 grade)	ppm	ASTM D5453	50 maximum	–	–	–	–
Sulfur (S 500 grade)	ppm	ASTM D5453	500 maximum	500 maximum	ASTM D5453	–	–
Carbon	wt%	ASTM D975	87	77	ASTM PS 121	–	–
Hydrogen	wt%	ASTM D975	13	12	ASTM PS 121	–	–
Oxygen	wt%	ASTM D975	0	11	ASTM PS 121	–	–

Sodium and potassium	mg/kg	–	–	–	–	5 maximum	EN 14108, EN 14109
Methanol content	%mass	–	–	–	–	0.2 maximum	EN 14110
Ester content	%mass	–	–	–	–	96.5 minimum	EN 14103
Linolenic acid methly ester	%mass	–	–	–	–	12 maximum	EN 14103
Polyunsaturated (³ 4 double bonds) methyl esters	%mass	–	–	–	–	1 maximum	EN 14104
Alkaline metals (Na+K)	mg/kg	–	–	–	–	5 maximum	EN 14108, EN 14109, EN 14538
Alkaline metals (Ca+Mg)	mg/kg	–	–	–	–	5 maximum	EN 14538
BOCLE scuff	g	ASTM D975	2000–5000	> 7000	ASTM PS 121		
Conductivity at ambient temp	pS/m	ASTM D2624	50 m minimum at ambient temp. (all diesel held by a terminal or refinery for sale or distribution)	–	–	–	–
Polyaromatic hydrocarbons (PAHs)	% m/m	IP391	11 maximum	–	–	–	–
Total contamination	mg/kg	–	–	24	ASTM D 5452	24	EN 12662

9.6. Density

Density is the relationship between the mass and volume of a liquid or a solid and can be expressed in units of grams per liter (g/L). The density of diesel oil is important because it gives an indication of the delay between the injection and combustion of the fuel in a diesel engine (ignition quality) and the energy per unit mass (specific energy). This can influences the efficiency of the fuel atomization for airless combustion systems [136,144,151,153]. ASTM Standard D1298 and EN ISO 3675/12185 test method are used to measure the density of the biodiesel. According to these standards, density should be tested at the temperature reference of 15 °C [138]. From Table 13, it has been found that *Madhuca indica* methyl ester has the highest density of 916 kg/m^3 and the lowest is *Hevea brasiliensis* (rubber seed oil) methyl ester (860 kg/m^3).

9.7. Acid number

The acid number is a measure of the amount of carboxylic acid groups in a chemical compound, such as a fatty acid, or in a mixture of compounds [151]. Acid number can provide an indication of the level of lubricant degradation while the fuel is in service [150]. Acid value or neutralization number is expressed as mg KOH required to neutralize 1 of fatty acid methyl esters and is set to a maximum value of 0.5 mg KOH/g in the European standard (EN 14104) and ASTM D 664 [51,138,154]. Higher acid content can cause severe corrosion in fuel supply system and internal combustion engine. From Table 13, it has been shown that the lowest acid number is 0.001 mg KOH/g for *Terminalia catappa* and the highest is 2.141 mg KOH/g for *Cuphea viscosissima.*

9.8. Carbon residue

Carbon residue test is used to indicate the extent of deposits resulting from the combustion of a fuel. Carbon residue which is formed by decomposition and subsequent pyrolysis of the fuel components can clog the fuel injectors. Biodiesel made from the vegetable oil feedstock has a carbon residue limit of Max. 0.050% (m/m) according to ASTM D 4530 and Max. 0.3% (m/m) according to EN ISO 10370 [51,138,150]. From Table 13, it can be seen that *Hibiscus sabdariffa* L. (roselle) has the highest carbon residue of 0.84 %mass while *Terminalia belerica* Robx. has the lowest of 0.00085 %mass.

9.9. Iodine number

The iodine number is an index of the number of double bonds in biodiesel which determines the unsaturation degree of the biodiesel. This property can greatly influence the oxidation stability and polymerization of glycerides. This can lead to the formation of deposits in diesel engines injectors. Iodine value is directly correlated to biodiesel viscosity, cetane number and cold flow characteristics (cold filter plugging point). The iodine number is set to a maximum value of 120 mg I_2/g according to EN 14111 [138,151]. In this review, *Simarouba glauca* (paradise tree) has been found to have the lowest iodine number of 46 mg I_2/g and the highest is 144 mg I_2/g for *Hevea brasiliensis.*

9.10. Calorific value

Calorific value is an important parameter in the selection of a fuel. The caloric value of biodiesel is lower than of diesel because of its higher oxygen content [76,77,147]. From Table 13, it can be seen that the lowest calorific value is 35.56 MJ/kg for

Table 11
Standard and quality of biodiesel in selected countries [235].

Fuel property	Unit	Indonesia (SNI Biodiesel No. 04-7182-2006)			Malaysia (MS 2008:2008)			Thailand (DOEB: 2009)			Vietnam (TCVN 7717: 2007)			China (GB/T20828-2007)			Republic of Korea (KS M)			Japan (JIS K2390:2008)		
		Min	Max	Test method	Min	Max	Test method	Min	Max	Test method	Mini	Max	Test method	Min	Max	Test method	Min	Max	Test method	Min	Max	Test method
Density	kg/m3	850 (40 °C)	890 (40 °C)	ASTM D1298, ISO 3675	860 (15 °C)	–	ISO 3675,ISO 12185,ASTM D 4052	860 (15 °C)	900 (15 °C)	ASTM D 1298	860 (15 °C)	900 (15 °C)	TCVN (ASTM D 1298)	820	900	GB/T2540	860	900	ISO 3675 (KS M 2002), ISO 12185	860 (15 °C)	900 (15 °C)	JIS K 2249
Kinematic viscosity (40 °C)	mm2/s (cSt)	2.3	6.0	ASTM D 445, ISO 3104	3.50	5.00	ISO 3104 MS 1831	3.50	5.00	ASTM D 445	1.9	6	TCVN (ASTM D 445)	1.9	6.0	GB/T 265	1.9	9–5.0	ISO 3104 (KS M 2014)	3.50	5.00	JIS K 2283
Cetane number		51	–	ASTM D 613, ISO 5165	51	–	ISO 5165, MS 1895	51	–	ASTM D 613	47	–	TCVN (ASTM D 613)	49	–	GB/T386	–	–	–	51	–	JIS K 2280
Flash point	°C	100	–	ASTM D 93, ISO 2710	120	–	ISO 3679e, MS 686	120	–	ASTM D 93	130	–	TCVN (ASTM D 93)	130	–	GB/T261	120	–	ISO 3679 (KS M 2010)	120	–	JIS K 2265
Cloud point	°C	–	–	ASTM D2500	–	–	–	–	–	–	–	Report	TCVN (ASTM D 2500)	–	–	–	–	–	–	–	–	–
Pour point	°C	–	18	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Agreement between producer and distributor		
CFPP	°C	–	–	–	–	15	EN 116	–	–	–	–	–	–	–	Report	SH/T0246	–	0	KS M 2411			
Copper strip corrosion	Rating (3 hours at 50 °C)	No 3		ASTM D 130, ISO 2160	Class 1		ISO 2160, MS 787	No.1		ASTM D 130	No.1		TCVN (ASTM D 130)	–	1	GB/T5096	No. 1		ISO 2160 (KS M 2018)	Class – 1		JIS K 2513
Carbon residue		–	–	–	–	–	–	–	–	–	–	0.05	TCVN (ASTM D 4530)	–	–	–	–	–	–	–	0.3	JIS K 2270
in undistilled sample, or	% (m/m)	–	0.05	ASTM D 4530, ISO 10370	–	0.30	ISO 10370, ASTM D 4530	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
in 10 % distillation residue	% (m/m)	–	0.3		–	0.05		–	0.3	ASTM D 4530	–	–	–	–	–	–	–	0.1	KS M ISO 10370	–	–	–
Water content	mg/kg	–	–	–	–	500	ISO 12937, ASTM E 203, ASTM D 1160		500	EN ISO 12937	–	–	–	–	0.05	SH/T0246	–	–	–	–	500	JIS K 2275
Water and sediment	vol%	–	0.05	ASTM D2709	–	–	–	–	–	–	–	0.05	TCVN (ASTM D 2709)	–	None	GB/T511	–	0.05	KS M 2115	–	–	–
90% (v/v) recovered at distillation temperature	°C	–	360	ASTM D1160	–	–	–	–	–	–	–	360	TCVN (ASTM D 1160)	–	360	GB/T6536	–	–	–	–	–	–
95% (v/v) recovered at distillation temperature	°C	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ash content (sulfated ash)	% (m/m)	–	0.02	ASTM D 874, ISO 3987	–	0.02	–	–	0.02	ASTM D 874	–	0.02	TCVN (ASTM D 874)		0.02	GB/T2433	–	0.01	KS M ISO 6245	–	0.02	JIS K 2272
Sulfur content	pm-m (mg/kg) m	–	100	ASTM D5453, ISO 20884	–	10.0	–	–	0.0010	ASTM D 2622	–	0.05	TCVN (ASTM D 5453)	0.005	0.05	SH/T0689	–	10	ISO 20846,ISO 20884 (KS M 2027)	–	10	JIS K 2541–1, –2, –6 or –7
		–	10			10.0		–	0.0010		–	0.001		–	–	–	–	10	EN 14107	–	10	EN 14107

Phosphorous content	pm-m (mg/kg) m (% m/m)			AOCS Ca 12–55, FBI –A05–03			EN 14107, ASTM D 4951			ASTM D 4951			TCVN (ASTM D 4951)									
Acid number	mg-KOH/g	–	0.8	AOCS Cd 3–63, FBI-A01–03	–	0.5	EN 14104, MS 2011	–	0.50	ASTM D 664	–	0.05	TCVN (ASTM D 664)	–	0.8	GB/T 264		0.5	KS M ISO 6618	–	0.5	JIS K 2501or JIS K 0070
Free glycerol	%(m/m)	–	0.02	AOCS Ca 14–56, FBI-A02–03	–	0.02	EN 14105, EN 14106, ASTM D 6584	–	0.02	EN 14105	–	0.02	TCVN (ASTM D 6584)	–	0.02	ASTM D 6584		–	–	–	0.02	EN 14105 or EN 14106
Total glycerol	%(m/m)	–	0.24	AOCS Ca 14–57, FBI-A03–03	–	0.25	EN 14105, ASTM D 6584	–	0.25	EN 14105	–	0.24	TCVN (ASTM D 6584)	–	0.24	ASTM D 6584		0.25	EN 14105 (KS M 2412)	–	0.25	EN 14105
Methyl ester content	% wt	–	–	–	–	–	–	96.5	–	EN 14103	–	–	–	–	–	–	–	–	–	–	–	–
Ester content	%(m/m)	–	96.5	Calculated, FBI-A03–03	96.5	–	EN 14103	–	–	–	96,5	–	TCVN (EN 14103)	–	–	–	96.5	–	–	96.5	–	EN 14103
Iodine number	%(m/m) (g-I2/100 g)	–	115	AOCS Cd 1–25, FBI-A04–03	–	110	–	–	120	EN 14111	–	120	TCVN (EN 14111)	–	–	–	–	–	–	–	120	JIS K 0070
Total contamination	mg/kg	–	–	–	–	24	EN 12662, ASTM D 5452	–	24	EN 12662	–	–	–	–	–	–	–	–	–	24	–	EN 12662
Oxidation stability (110 °C)	h	–	–	–	6.0	–	EN 14112	10		EN 14112	6	–	TCVN (EN 14112)	6	–	EN 14112	6	–	EN 14112	Agreement between producer and distributor		
Linolenic acid methyl ester	% (m/m)	–	–	–	–	12.0	EN 14111	–	12.0	EN 14103	–	–	–	–	–	–	–	–	–	–	12	EN 14103
Polyunsaturated (≥ 4 double bonds) methyl esters	%mass	–	–	–	1.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	N.D	–	–
Methanol content	%mass	–	–	–	–	0.2	EN 14110	–	0.20	EN 14110	–	–	–	–	–	–	0.2		EN 14110	–	0.2	EN 14110
Monoglyceride content	%mass	–	–	–	–	0.8	EN 14105, ASTM D 6584	–	0.8	EN 14105	–	–	–	–	–	–	–	–	–	–	0.8	EN 14105
Diglyceride content	%mass	–	–	–	–	0.2	EN 14105, ASTM D 6584	–	0.2	EN 14105	–	–	–	–	–	–	–	–	–	–	0.2	EN 14105
Triglyceride content	%mass	–	–	–	–	0.2	EN 14105, ASTM D 6584	–	0.2	EN 14105	–	–	–	–	–	–	–	–	–	–	0.2	EN 14105
Group I metal (Na+K)	mg/kg	–	–	–	–	5.0	EN 14108, EN 14109	–	5.0	EN 14108, EN 14109, prEN 14538	–	5.0	TCVN (EN 14108 and EN 14109)	–	–	–	–	5	EN 14108, EN 14109	–	5.0	EN 14108 and EN 14109
Group II metals (Ca+Mg)	mg/kg	–	–	–	–	5.0	EN 14538		5.0		–	5.0		–	–	–	–	5	EN 14538	–	5.0	EN 14538
Halphen test		–	Negative	AOCS Cd 1–26, FBI-A06–03	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	

SNI=standard nasional Indonesia; MS=Malaysia standard; DOEB=Thailand standards; GB=Guobiao National standards China; JIS=Japan industrial standards; KSM=Korea standard method (Republic of Korea).

Pongamia pinnata (karanja) and the highest is 47.38 MJ/kg for *Simmondsia chinensis* (jojoba).

9.11. Sulfur content

Combustion of fuel containing sulfur causes emissions of sulfur oxides. Most of vegetable oils and animal fat-based biodiesel have very low levels of sulfur content. However, specifying this parameter is important for engine operability [1,4,7,137,138,155]. The sulfur content of various non-edibles methyl esters has been given in Table 13.

9.12. Sulfate ash content

The Ash content describes the amount of inorganic contaminants such as abrasive solids and catalyst residues, and the concentration of soluble metal soaps contained in a fuel sample [150]. Table 13 shows the sulfate ash content of various non-edible methyl esters.

9.13. Water and sediment content

The presence of water and sediment has two forms, which are either dissolved water or suspended water droplets. While biodiesel is generally considered to be insoluble in water, it actually takes up considerably more amount of water than diesel fuel. On other hand, water content of biodiesel reduces the heat of combustion and will cause corrosion of vital fuel system components fuel pumps, injector pumps, fuel tubes, etc. Moreover, sediment may consist of suspended rust and dirt particles or it may originate from the fuel as insoluble compounds formed during fuel oxidation [1,150,156]. The standards of water content and sediment for biodiesel are ASTM D 2709 and EN ISO 12937 respectively. Both limit the amount of water to be max. 0.05 (v%) [51,138]. Table 13 highlights the water and sediment content of various non-edibles methyl esters.

9.14. Free and total glycerin

Free and total glycerin is a measurement of how much triglyceride remains unconverted into methyl esters. Total glycerin is calculated from the amount of free glycerin, monoglycerides, diglycerides, and triglycerides. Structurally, triglyceride is a reaction product of a molecule of glycerol with fatty acid molecules, yielding three molecules of water and one molecule of triglyceride [51,143,157]. The characteristics of free and total glycerin for a variety of non-edible vegetable oils have been examined and presented in Table 13 in this review. The free glycerin of *Brassica carinata* (ethiopian mustard) has the highest value of 38%mass and *Azadirachta indica* (neem) has the lowest of 0.0% mass. The presence of monoglycerides, diglycerides and triglycerides are in the range of 0.0–0.78%mass. Furthermore, biodiesel produced from *Guizotia abyssinica* L. (niger) has the lowest total glycerin of 0.017%mass while the highest is 0.507%mass found in *Ricinus communis* (castor).

9.15. Phosphorus, calcium and magnesium content

Phosphorous, calcium, and magnesium are minor components which are typically associated with phospholipids and gums that may act as emulsifiers or cause sediment, lowering yields during the transesterification process [158]. The specifications from ASTM D6751 state that phosphorous content in biodiesel must be less than 10 ppm, and calcium and magnesium combined must be less than 5 ppm. Phosphorous is determined using ASTM D 4951 and EN 14107, Calcium and Magnesium are determined using EN Standard 14538 [51,138]. Table 13 highlights the phosphorous, calcium, and magnesium contents of various non-edible oil methyl esters.

9.16. Moisture impurities and unsaponifiables (MIU) content

Moisture, impurities and unsaponifiables (MIU) are the amount of water, filterable solids (such as bone fragments, food particles or other solids), and other non-triglycerides in an oil which cannot be converted to mono alkyl fatty esters by esterification or transesterification. Hence, MIUs must be removed before biodiesel production or during ester purification [159]. Moisture is a minor component that can be found in all feedstocks. Moisture can react with the catalyst during transesterification which can lead to soap formation and emulsions [51]. The moisture in the biodiesels is measured in accordance to ASTM E203 and has specification of 0.050 wt% maximum [51,138]. The lowest value of moisture content of non-edible methyl ester is 0.015 wt% for Rice brand while the highest is found in *Lesquerella fendleri* (0.073 wt%).

10. Engine performance and emission characteristics

10.1. Effects of blending vegetable oils on engine performances and emissions

The idea of running straight vegetable oils (SVO) to power an engine is not new. In fact, Mr. Rudolf Diesel designed the diesel engine to be fueled by peanut oil 100 years ago. However, modern diesel engines are far different from the early prototypes. The advent of the injection pump, high pressure fuel systems and various high tolerance parts require that a less viscous fuel must be employed. In addition, polymerizing of straight vegetable oil can lead to the build-up of carbon deposits inside the engine, oil ring sticking, injector cocking as well as gelling of the engine lubricant oil in diesel engines. It has been reported that there is a negative impacts of SVO on the engine lubricant. This is caused by the very high boiling point and viscosity of SVO relative to the required boiling range for diesel fuel. Therefore, all of these problems will lead to reduced engine life span. Fig. 4 shows that even small percentages of oil mixed with standard diesel fuel can dramatically increase the coking index of the fuel blend [1,160,161].

Singh and Singh [4] and Basha et al. [162] indicated that short-term engine tests using vegetable oils as fuels were very promising while problems occurred in long term durability tests. These problems are associated mainly with high viscosity of vegetable oil resulting in higher carbon built up and lubricating oil contamination resulting eventually in engine failure. Therefore, Basha et al. [162] concluded that vegetable oils should be either chemically altered or blended with diesel to prevent the engine failure.

No [2] indicates that the appropriate blend of vegetable oil with diesel is required to ensure optimum performance, lower emission and best combustion characteristics depends on the particular feedstock and the subsequent biodiesel formulation. Most of studies and researches concluded that a 20% blend of vegetable oil and biodiesel with diesel works satisfactorily in the existing engine design and parameters. The author reviewed the engine performance and emissions result for several non-edible oils such as *Jatropha curcas*, *Pongamia pinnata* (karanja), *Madhuca indica* (mahua), Linseed, Rubber seed, cotton seed, neem oil respectively. The author pointed out that all the application methods of *Jatropha curcas* oil as a substitute for CI engine give the lower brake thermal efficiency and higher specific fuel consumption compared to diesel fuel operation. Moreover, HC, CO

Table 12
Summary of some important characteristics of biodiesel [112].

Fuel characteristic	Effects
Cetane number	(i) To measure of ignition quality of diesel fuels (ii) The high cetane number implies short ignition delay (iii) Higher molecular weight normal alkanes have high cetane numbers (iv) It influences both gaseous and particulate emissions (i) The cetane index which is very close to cetane number is calculated based on 10%, 50%, 90% distillation temperatures and specific gravity (i) The fuels with high auto ignition temperatures are more likely to cause diesel knock
Distillation rang	(i) It affects fuel performance and safety (ii) It is important to an engine's start and warm up (ii) Presence of high-boiling components affect the degree of formation of solid combustion deposits (iv) It is needed in the estimation of cetane index
Specific gravity	(i) It is required for the conversion of measured volumes to volumes at standard temperature of 15 °C (ii) It is used in the calculation of cetane index
Heat of combustion	(i) To measure of energy available in a fuel (ii) A critical property of fuel intended for use in weight-limited vehicles
Flash point	(i) It indicates the presence of highly volatile and flammable materials (ii) To measures the tendency of oil to form a flammable mixture with air (iii) It is used to assess the overall flammability hazard of a material
Viscosity	(i) Proper viscosity of fuel required for proper operation of an engine (ii) Important for flow of oil through pipelines, injector nozzles and orifices (ii) Effective atomization of fuel in the cylinder requires limited range of viscosity of the fuel to avoid excessive pumping pressures
Contamination (water/sediment)	(i) It causes corrosion of equipment (ii) It causes problems in processing (iii) It is required to accurately measure net volumes of actual fuel in sales, taxation, exchanges and custody transfer
Copper-strip corrosion	(i) To measure to assess relative degree of corrosively (ii) It is indicates the presence of sulfur compounds
Cloud point, pour point cold-filter plugging point	(i) To measure the performance of fuels under cold temperature conditions (ii) It is used as quality control specification or low temperature handling indicators for large storage tanks and pipelines at refineries and terminals
Carbon residue	(i) It correlates with the amount of carbonaceous deposits in the combustion chamber (ii) Greater carbon deposits expected for higher values of carbon residue
Particulate matter	(i) It indicates the potential of emission of particulate matter (ii) It contains primarily carbon particles (iii) The Soot (carbonaceous particulates formed from gas-phase processes) particles absorb and carry carcinogenic materials into environment as emission and can cause an ill effect on human health. Excessive soot particles might clog the exhaust valves
Ash	(i) Results from oil, water-soluble metallic compounds or extraneous solids, such as dirt and rust (ii) It can be used to decide product's suitability for a given application
Sulfur	(i) It is controlled to minimize corrosion, wear and tear (ii) It causes environmental pollution from their combustion products (iii) It is corrosive in nature and causes physical problems to engine parts

and NO_x emissions are higher and smoke level is lower than those of dual fuel operation with diesel.

Rakopoulos et al. [163] tested a variety of vegetable oils blends of 10% and 20% respectively including cotton seed oil in in a standard, fully instrumented, four stroke, direct injection (DI), Ricardo/Cussons 'Hydra' Diesel engine located at the authors' laboratory. The authors found that specific fuel consumption was a little higher than that for the corresponding diesel fuel in both medium and high loads. Smoke (soot) density and CO emissions were also increased with the use of vegetable oils compared to that of neat diesel in both medium and high loads. HC emissions increased slightly with 10% blends. However, with 20% blends no significant differences have been observed. NO_x, emission was lower in case of vegetable oil blends than neat diesel in both medium and high loads. The authors concluded that vegetable oil blends with normal diesel fuel can be used safely and advantageously in small blending ratios with diesel fuel.

Babu and Devaradjane [164] showed that compared to No. 2 diesel fuel, all of the vegetable oils are much more viscous, much more reactive to oxygen and has higher cloud point and pour point. They also found that vegetable oils and their biodiesels offer lower engine noise, and lower smoke, HC, and CO, slightly higher NO_x and higher thermal efficiency compared with diesel fuel.

Agarwal et al. [129] evaluated the engine performance and emission characteristics of linseed oil, mahua oil and rice bran oil in a stationary single cylinder, four stroke diesel engine and compared them with mineral diesel fuel. These oils were blended with diesel in different proportions. The obtained results showed that the performance and emission parameters such as thermal efficiency, BSEC and smoke density for different fuel blends were found to be very close with some variations to diesel. For instance, almost similar thermal efficiencies have been recorded for all oil blends with mineral diesel. The authors concluded that vegetable oil blends can be used in compression ignition engines in rural areas for agriculture, irrigation and electricity generation.

Pramanik [126] analyzed the performance using the blends of diesel and Jatropha oil in a single cylinder compression

Table 13
Properties of biodiesel produced from non-edible oil feedstocks

Feedstock non-edible methyl ester	Pour point (°C)	Cloud point (°C)	Flash point (°C)	CFPP (°C)	Viscosity at 40 °C (mm2/s)	Specific gravity	Cetane number	Calorific value (Mj/kg)	Cold soak filtration (s) (mL Remaining)	Density
	2	14.4	> 160	11	2.7	–	51–57.87	39.81	130 in 720	0.868 g/cc3
Asclepias syriaca (milkweed)	−6	−0.95	–	–	4.6–5.2	–	50	–	–	–
Brassica carinata (ethiopian mustard)	–	–	> 120	–	4.5	–	52	–	–	879 kg/m3
Balanites aegyptiaca (desert date)	–	3–7	122–131	1–3	3.7–4.2	–	53.56	–	–	870–890 kg/m3
Calophyllum inophyllum	4.3	13.2	151	–	4	–	57.3	–	–	888.6 kg/m3
Camellia japonica	–	–	193	–	4.7	–	54	–	–	877 kg/m3
Camelina sativa	−8	1.5	> 160	−1	4.365	–	–	–	223	–
Cuphea viscosissima	–	–	–	–	–	–	–	–	–	–
Eruca sativa gars	−10	–	127	–	5	0.879	49	38.67	–	–
Eruca sativa L. (taramira)	–	–	52	–	5.9	–	48	–	–	0.8811 at 15 °C g/cm3
Euphorbia lathyris.L	–	–	181	−11	4.63	–	59.6	–	–	876 at 20 °C kg/m3
Guizotia abyssinica L. (niger)	–	4	157	–	4.30	–	57	–	–	–
Hevea brasiliensis (rubber seed oil)	−8	4	130	–	5.81	0.842	–	36.5	–	860 kg/m3
Hibiscus sabdariffa L. (roselle)	−1	–	> 130	–	4.58	–	–	–	–	880.1 kg/m3
Idesia polycarpa var. vestita fruit	–	−4	> 174	−2	4.12	–	47	–	–	886.2 kg/m3
Jatropha curcas L.	–	4	163		4.4	–	57.1	41.17	–	880 kg/m3
Lesquerella fendleri	–	−11.6	> 160	−6	10.02	–	–	–	> 720 (190 mL)	–
Madhuca indica (mahua)	6	5	129	–	3.98	0.916	51	39.4	–	916 kg/m3
Michelia champaca	–	–	–	–	–	–	50.28	–	–	–
Nicotiana tabacum (tobacco)	–	–	165.4	−5	4.23	–	51.6	39.81	–	888.5 kg/m3
Pongamia pinnata (karanja)	–	–	180	−7	4.85	0.878	58	35.56	–	0.89 g/cc
Putranjiva roxburghii	−3	–	48	–	–	–	54.99	39.58	–	–
Pongamia glabra (koroch seed) (B40)	6	–	55	–	3.28	0.918	45.39	43.42	–	0.8661 g/cc
Rice brand	–	0.3	> 160	−3	4.95	–	73.6	36.05	111	877 kg/m3
Ricinus communis (castor)	–	−13.4	> 160	7	15.25	–	–	38.7	> 720 (216 mL)	0.913 g/ml
Simarouba glauca (paradise tree)	2	–	141.2	–	5.4	–	64	–	–	0.8752 g/cc
Simmondsia chinensis (jojoba)	–	–	61	–	19.2	–	63.5	47.38	–	0.866 g/ml
Sapium sebifeum Lin. Roxb (stillingia)	–	−13	137	−10	4.81	–	50	–	–	0.900 g/cm3
Sterculia feotida L.	0.14	–	162	–	6	–	54	–	–	0.875 g/cm3
Terminalia catappa	6	–	90	–	4.3	–	57.1	36.97	–	873 at 20 °C g/cm3
Terminalia belerica Robx.	6	–	90	–	5.17	–	53	39.22	–	882.8 kg/m3
Thlaspi arense L. (field Pennycress)	−18	−10	–	−17	5.24	–	59.8	–	–	–
Vernicia fordii	–	–	185	–	2.5	–	53	–	–	864 kg/m3

Iodine number (g I2/100 g)	Sulphated ash content (%mass)	Ash content (%mass)	Carbon residue (%mass)	Water and sediment (vol%)	Visual inspection	Free glycerin (%mass)	Monoglycerides (%mass)	Diglycerides (%mass)	Triglycerides (%mass)	Total glycerin (%mass)	Copper corrosion
–	< 0.005	–	0.105	< 0.005	3	0.000	0.338	0.474	0.000	0.158	1b
–	–	–	–	–	–	–	–	–	–	–	–
128	< 0.01	–	0.09	–	–	38	0.53	0.13	0.07	–	–
97–100	–	–	0.1–0.2	410–450 (mg/kg)	–	–	–	–	–	–	1
85	0.026	–	0.434	0	–	–	–	–	–	0.232	1b
–	–	–	0.02	–	–	0.01	–	–	–	0.04	–
–	< 0.005	–	0.075	< 0.005	1	0.002	0.222	0.125	0.022	0.080	1a
–	–	–	–	–	–	0.002	0.780	0.089	0.000	0.218	–
–	–	–	–	–	–	–	–	–	–	–	–
–	–	–	–	0.05	–	–	–	–	–	–	1
–	–	–	–	400 mg/kg	–	0.01	–	–	–	0.09	1a
–	0.0016	–	0.018	–	–	0.002	–	–	–	0.017	1
144	–	0.01	–	–	–	–	–	–	–	–	–
62	< 0.005	–	0.84	< 0.005	–	0	0.5733	0.0163	0	0.11	1a
–	–	–	0.3	–	–	–	–	–	–	–	1a
–	Max. 0.02	–	–	0.05	–	0.01	–	–	–	0.02	1
–	0.01	–	0.109	0.075	2	0.055	0.559	0.710	0.023	0.307	1a

74.2	–	0.01	0.20	0.04	–	–	–	–	–	–	–
104.0	–	–	–	–	–	–	–	–	–	–	–
136	0.0004	–	0.029	–	–	0.002	0.54	0.13	0.17	0.23	1a
89	0.005	–	0.002	–	–	0.022	0.65	0.16	0.12	–	1a
82.9	–	–	< 0.1	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	–	–
–	< 0.005	–	0.047	< 0.005	1	0.001	0.281	0.059	0.000	0.083	1a
–	0.034	–	0.110	< 0.005	1	0.367	0.258	0.479	0.023	0.507	1a
46	–	–	0.18	0.05	–	–	–	–	–	–	1
–	0.01	0.037	0.26	300 mg/kg	–	0.01	0.359	–	0.000	0.09	1a
–	–	–	–	–	–	0.000	0.359	0.423	0.000	0.156	–
98	–	–	–	–	–	–	–	–	–	–	–
83.2	–	–	–	–	–	––	–	–	–	–	–
77.8	–	0.0005	0.0085	–	–	–	–	–	–	–	–
–	–	–	–	–	–	0.005	–	–	–	0.041	–
–	–	–	0.02	–	–	0.01	–	–	–	0.04	–

Phosphorous (ppm)	Calcium (ppm)	Magnesium (ppm)	Acid number (mg KOH/g)	Methanol content (mg/kg)	Ester content (wt%)	Moisture (wt%)	Sulfur (ppm)	Oxidation stability (h)	Distillation temperature (%)	Lubricity (HFRR;mm)	Refs.
< 0.1	–	0.9	0.649	–	–	0.036	473.8	7.1	–	–	[25,51,72]
–	0.3	–	–	–	–	–	–	–	–	–	[25]
–	–	–	0.08	50	13	–	< 10 mg/kg	–	–	–	[141]
1.1–2.2	–	1.0–1.5	–	–	–	–	2–5 mg/kg	–	–	124–126	[142]
0.223	–	–	–	–	–	–	–	–	–	–	[25,104]
–	–	–	0.16	–	97.7	–	–	–	–	–	[143]
< 0.1	0.8	1.1	0.338	–	–	0.04	0.6%mass	1.7	–	122	[51,146]
< 0.1	< 0.1	0.2	2.141	–	–	0.050	–	13.3	–	–	[51]
–	–	–	–	–	–	–	–	–	–	–	[14]
–	–	–	0.40	–	97	–	0.02%mass	8	–	–	[98]
–	–	–	0.19	97.61	97.6	–	–	10.4	–	–	[70]
< 0.001 %mass	max. < 1 mg/kg	max. < 1 mg/kg	0.15	0.003	–	–	0.003 %mass	3.23	1.02	–	[18]
–	–	–	0.9	–	–	–	–	–	–	–	[74,76]
–	–	–	0.43	0.01	–	–	0.00021 %mass	2.58	–	–	[99]
–	–	–	0.27	–	–	–	–	–	354.5	–	[20]
< 0.001 %mass	–	–	0.48	–	–	–	max. 0.005 %mass	Min. 6 h	–	–	[228,236]
< 0.1	< 0.1	0.7	0.630	–	–	0.073	180	10.5	–	–	[51]
–	–	–	–	–	–	–	–	–	–	–	[2,25,147,161,171,183]
–	–	–	–	–	–	–	–	–	–	–	[16]
4 mg/kg	< 2 mg/kg	< 2 mg/kg	0.3	< 0.01	98.6	–	8 mg/kg	0.8	–	–	[83,84,87]
–	–	–	0.42	0.005	–	–	0.003 %mass	6	348	–	[25,47,188]
–	–	–	–	–	–	–	–	–	–	–	[16,92]
–	–	–	–	–	–	–	274	–	–	–	[237]
< 0.1	0.6	0.9	0.586	0.29	–	0.015	6 %mass	0.4	–	–	[51,184]
< 0.1	< 0.1	< 0.1	0.996	–	–	0.053	1.3 %mass	1.1	–	–	[51,157]
–	–	–	–	–	–	–	0.13 %mass	–	–	–	[238]
< 0.1	4	2.4	–	–	–	0.026	0.3 %mass	56.9	–	–	[51,239]
< 0.1	0.5	0.4	0.708	–	–	0.052	1.5 %mass	0.6	–	–	[15,51,70]
–	–	–	0.14	–	–	–	–	–	–	–	[103]
–	0.5	0.4	0.001	–	–	0.067	13.3 %mass	0.4	–	–	[25,144]
–	–	–	0.23	–	–	–	96	–	–	–	[28]
0.0	–	–	0.04	–	–	–	7	4.4	–	125	[139]
–	–	–	0.19	–	96.1	–	–	–	–	–	[143]

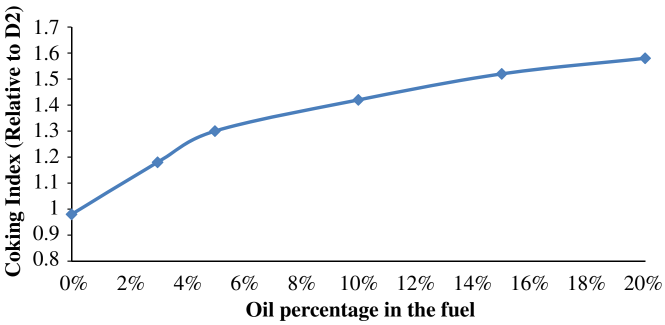


Fig. 4. Effect of increasing the blend of a vegetable oil into diesel fuel on the tendency to form carbon deposits [160].

ignition engine. A significant improvement in engine performance parameters such as SFC and brake thermal efficiency was reported when blending vegetable oil to diesel compared with pure vegetable oil. The specific fuel consumption and the exhaust gas temperature were reduced due to decrease in viscosity of the vegetable oil. Blends with a lower percentage of vegetable oils showed slightly higher exhaust gas temperatures when compared with diesel in an engine running. Acceptable thermal efficiencies of the engine were found within blends containing up to 50% volume of Jatropha oil. From the properties and engine test results it has been established that 40–50% of Jatropha oil can be substituted for diesel without any engine modification. However, further study is required to determine the long-term durability of the engine.

Forson et al. [130] tested 97.4%/2.6%; 80%/20%; and 50%/50% by volume blends of diesel and Jatropha oil on a single-cylinder direct injection engine. The most significant outcome from the study was that the 97.4% of diesel and 2.6% of Jatropha fuel blend produced maximum values of the brake power and brake thermal efficiency as well as minimum values of the specific fuel consumption, exhaust gas temperature, carbon monoxide and carbon dioxide. Moreover, the authors suggested the use of 2.6% by volume of Jatropha oil as an ignition accelerator additive for diesel fuel. They concluded that 97.4% of diesel and 2.6% of jatropha fuel blend competed favorably with diesel fuel and offers a reasonable and better result for substitute pure diesel fuel.

Agarwal and Agarwal [128] study the effect of reducing Jatropha oil viscosity by preheating and blending Jatropha oil with diesel respectively. The test was conducted in a single cylinder, four stroke, constant speed, water cooled, direct injection diesel engine typically used in agricultural sector was used for the experiments. The results obtained when preheating show that BSFC and exhaust gas temperatures for unheated Jatropha oil was found to be higher compared to diesel and heated Jatropha oil. Moreover, thermal efficiency was lower for unheated Jatropha oil compared to heated Jatropha oil and diesel. CO_2, CO, HC, and smoke opacity were found to be close with diesel for preheated Jatropha oil. For blends, BSFC and exhaust gas temperature were found higher compared to diesel. Thermal efficiency was also found to be close to diesel for Jatropha oil blends. Emission parameters such as smoke opacity, CO_2, CO, and HC were found to have increased with increasing proportion of Jatropha oil in the blends compared to diesel. The authors concluded that either heating or blending Jatropha oil can be used in compression ignition engines in rural areas for agriculture, irrigation and electricity generation. Moreover, modified maintenance schedules can be adopted to control carbon deposits formed during long term usage of vegetable oils/blends.

Chauhan et al. [165] also investigated the effect of preheating Jatropha oil on engine performance and emissions. Experimental results show that the engine performance with unheated Jatropha oil is slightly inferior to the performance with diesel fuel. As fuel inlet temperature of Jatropha oil increased, viscosity decreased, the engine performance improved. Moreover, the authors found that the optimal fuel inlet temperature (FIT) was 80 °C which gives the best results considering brake thermal efficiency (BTE), Brake specific fuel consumption BSEC, gaseous emissions such as HC, CO, CO_2 and NO_x and durability and safe operation of the engine.

Kumar et al. [133] concluded the use of single fuel operation with neat Jatropha oil resulted in a slightly reduced thermal efficiency, increase in ignition delay and combustion duration, increase smoke and HC emissions and Lower heat release as compared to diesel. Moreover, they showed that using Jatropha oil methanol blend as compared to neat Jatropha oil resulted in an increase in brake thermal effciency from 27.4% to 28.1%, good reduction of exhaust gas temperature from 428 °C to 410 °C, Lowering of HC and CO emissions, reduced smoke levels from 4.4 to 4:1 BSU and Increase in ignition delay.

Haldar et al. [92] studied the possibility of utilizing pure *Putranjiva roxburghii* oil in Ricardo Variable Compression Diesel Engine. In this study, blends (10%, 20%, 30%, and 40% v/v) of pure Putranjiva oil and diesel are used. Their main findings indicate that up to 30% blends of pure *Putranjiva roxburghii* oil and diesel reduce the emissions such as CO, NO_x, smoke and particulates. The performance parameters such as brake thermal efficiency and BSFC are comparable to neat diesel. However, the blend above 30%, the brake thermal efficiency and BSFC will show inferior quality.

Ramadhas et al. [75] used rubber seed oil in a compression ignition engine. The experimental results showed that rubber seed oil is a promising alternative fuel for diesel engines. Brake thermal efficiency and specific fuel consumption were found acceptable with blends containing up to 80% of rubber seed oil. However, rubber seed oil blend fueled engine has higher carbon deposits inside combustion chamber than diesel fueled engine. This is attributed to the incomplete combustion of the fuel. Utilization of blends required frequent cleaning of fuel filter, pump and the combustion chamber. The study also concluded that 50–80% of rubber seed oil can be substituted for diesel easily in the compression ignition engines without any major modification and operational difficulties. Moreover, the authors recommended that rubber seed oil biodiesel blend fuel is more suitable for rural power generation.

Karthikeyan and Mahalakshmi [131] studied the performance, emission and combustion characteristics when using turpentine oil obtained from the resin of pine tree. The performance was done through DF (dual fuel) mode. Turpentine was inducted as a primary fuel through induction manifold and diesel was admitted into the engine through conventional fueling device as an igniter. The results showed that except volumetric efficiency, all other performance and emission parameters were better than diesel fuel within 75% load. The toxic gases like CO and Unburnt Hydrocarbon (UBHC) were slightly higher than DBL (diesel baseline). Around 40–45% smoke reduction was obtained with DF mode. The pollutant NO_x was found to be equal to that of DBL except at full load. The authors concluded that 60–65% replacement of diesel with turpentine is quite possible within 75% load.

Mani and Nagarajan [132] experimented waste plastic oil as a fuel in a single cylinder, four stroke, direct injection, diesel engine. The influence of injection timing on the performance, emission and combustion characteristics was investigated. The tests were performed at four injection timings (23°, 20°, 17° and 14° bTDC). The main findings of this study showed that the engine was able to run with 100% waste plastic oil when the injection timing was retarded from 23° bTDC to 14° bTDC. Cylinder peak pressure is found to be marginally lower. Moreover, it has been observed that

exhaust gas temperature, nitrogen oxides, carbon monoxide (25% reduction) and unburned hydrocarbon (30% reduction) decreased accordingly. However, the brake thermal efficiency, carbon dioxide and smoke increased under all the test conditions.

10.2. Effects of blending biodiesel on engine performances and emissions

Engine performance with biodiesel or its blends with diesel fuel depends largely on the combustion, air turbulence, air–fuel mixture quality, injector pressure, actual start of combustion and many other singularities that make test results vary from one engine to another. In addition, it can vary depending on the quality and origin of biodiesel as well as engine operating parameters like speed, load, etc. [166]. Generally, the blend of non-edible biodiesel with mineral diesel can be applied directly to CI diesel engines. However, the effect of using this biodiesel must be evaluated by determining engine power/torque, brake thermal efficiency, brake specific fuel consumption and emissions production. Extensive research has been conducted worldwide to utilized non-edible biodiesel as a possible fuel for use in a diesel engine. Series of experiments by using blended non-edible biodiesel for compression ignition engines have focused on engine performances and emissions. This section reviews the effects of blending non-edible biodiesel on engine performance and emission in CI diesel engines found from the literature.

Saravanan et al. [167] studied the combustion and emissions characteristics of crude rice bran methyl ester (CRBME) blend with no. 2 diesel oil (20/80 on volume basis) as a fuel in a stationary small duty direct-injection compression ignition engine. The study found that CRBME blend exhibits similar combustion characteristics as diesel with reduced smoke intensity and higher NO_x emission. The cylinder pressure was comparable to that of diesel. The delay period and the maximum rate of pressure rise for CRBME blend fuel were lower than those of diesel. The occurrence of maximum heat release rate advanced for blend fuel with lesser magnitude when compared with diesel. The brake specific fuel consumption of blend fuel was found to be only marginally different from that of the diesel. However, the fuel cost of biodiesel blend was higher than diesel fuel. They concluded that CRBME can be a potential resource that can be utilized as a CI engine fuel in blended form.

Sahoo et al. [168] presented the results of engine performance fueled with *Jatropha*, Karanja (*Pongamia pinnata* L.), Polanga (*Calophyllum inophyllum* L.) biodiesel. They observed that the maximum increase in power is observed for 50% Jatropha biodiesel and diesel blend at rated speed while the best brake specific energy consumption (BSEC) improvement is observed with 20% of Polanga biodiesel (PB). Smoke emission reduces with blends and speeds during full throttle performance test. During part throttle test mode, it has been observed that blends with higher percentage of biodiesel tend to decrease the exhaust smoke substantially. Noticeable reduction in HC and PM is seen with biodiesel and their blends. However, there is a slight increase in CO and NO_x.

Sahoo et al. [8] tested Polanga oil methyl ester (POME) with high speed diesel (HSD) in a single cylinder diesel engine. In this study, HSD and Polanga oil methyl ester (POME) fuel blends (20%, 40%, 60%, 80%, and 100%) were used for conducting the short-term engine performance tests at varying loads (0%, 20%, 40%, 60%, 80%, and 100%). The optimum engine operating condition was observed at 100% load for neat biodiesel. The 100% biodiesel improved the thermal efficiency of the engine by 0.1%. Brake specific energy consumption and the exhaust emissions were reduced. Decrease in the exhaust temperature of a biodiesel-fueled engine led to approximately 4% decrease in NO_x emissions for B_{100} biodiesel at full load. The authors concluded that Polanga based biodiesel can be adopted as an alternative fuel for the existing conventional diesel engines without any major hardware modifications in the system.

Özcanli et al. [111] investigated engine performance and emissions production of biodiesel obtained from terebinth (pistacia terebinthus). The test was carried out in a three-cylinder, four strokes, and direct-injection CI engine. Terebinth oil biodiesel (B)–diesel fuel (D) blends were tested in at full load condition. Power values showed a trend of decreasing with all biodiesel fuels at high engine speeds. Specific fuel consumption (SFC) values increased depending on the amount of biodiesel in the test fuels. Moreover, the authors found that the exhaust emissions profile of biodiesel fuels improved. CO and CO_2 emissions decreased up to 34.54% and 10.69% respectively. However, NO_x emissions increased up to 32.97%.

Basha and Anand [169] prepared biodiesel emulsion fuel by emulsification technique comprising 83% of Jatropha biodiesel, 15% of water, and 2% of surfactants with the aid of a mechanical agitator. The prepared biodiesel emulsion fuel is mixed with the alumina nanoparticles in the mass fractions of 25, 50, and 100 ppm respectively with the help of an ultrasonicator. The authors remarked that the prepared biodiesel emulsion fuels with/without alumina nanoparticles were stable for more than 5 days under idle conditions. The engine performance was carried out in a constant speed diesel engine in three phases using Jatropha biodiesel, Jatropha biodiesel emulsion fuel, and alumina nanoparticle blended Jatropha biodiesel emulsion fuels. The experimental results revealed a substantial enhancement in the performance and a reduction in harmful emissions for the biodiesel emulsion fuels compared to those of neat biodiesel. The incorporation of nanoparticles in the biodiesel emulsion fuel has also revealed an incremental better performance and reduced emissions than that of biodiesel emulsion fuel and biodiesel. Moreover, the addition of potential nanoparticles to the biodiesel emulsion fuels has imparted reduced peak pressure, heat release rate, and ignition delay compared to that of neat biodiesel emulsion fuel operation. The brake thermal efficiency of JBDS15W100A (83% Jatropha biodiesel + 2% surfactant + 15% water + 100 ppm of alumina) fuel is high compared to that of other tested fuels. At the rated load, the maximum brake thermal efficiency of JBDS15W100A fuel is 29.4%, whereas it is 24.9% for the JBD fuel. The NO_x and smoke emissions are drastically reduced for the biodiesel emulsion fuels compared to that of Jatropha biodiesel. The magnitude of NO_x and smoke emission observed is 870 ppm and 49% for JBDS15W100A fuel, whereas it is 1282 ppm and 67% for JBD fuel at the full load, respectively. As a conclusion the authors indicated that the performance and the emission characteristics of the diesel engine are improved due to the incorporation of alumina nanoparticles in the biodiesel emulsion fuels.

Zhihao et al. [170] study the emission of Pistacia Chinensis Bunge Seed Biodiesel–Diesel Blends. Their findings were that CO, HC emissions and exhaust smoke of the engine fueled with biodiesel–diesel blends are lower than that of diesel, and decrease as the mixing proportion of biodiesel in the blends increases. The NO_x emissions of B_{10} and B_{20} are less than that of diesel and the amount of NO_x emissions for B_{30} is almost the same as for diesel.

Raheman and Ghadge [171] investigated the performance of biodiesel obtained from Mahua oil (B_{100}) and its blend with high speed diesel (HSD) in a Ricardo E6 engine. The main findings of this study were that the brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) increased and brake thermal efficiency (BTE) decreased with increase in the proportion of biodiesel in the blends and the loads. The smoke level and CO in exhaust emissions reduced, whereas NO_x increased with increase

in percentage of mahua biodiesel in the blends. However, the level of emissions increased with increase in engine load for all fuels tested. The authors concluded that that B_{100} could be safely blended with HSD up to 20% without significantly affecting the engine performance (BSFC, BTE, EGT) and emissions (Smoke, CO and NO_x) and thus could be a suitable alternative fuel for diesel.

Raheman and Ghadge [172] investigated the performance of biodiesel obtained from Mahua oil in a Ricardo E6 engine at varying compression ratio (CR), injection timing (IT) and engine loading (L). They observed an increase in the brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT), whereas brake thermal efficiency (BTE) decreased with increase in the proportion of biodiesel in the blends at all compression ratios (18:1–20:1) and injection timings (35–45° before TDC). The author also reported that the blend of biodiesel (B_{20}) is the most suitable fuel blend for controlling air pollution.

Saravanan et al. [161] reported a test of single cylinder, four stroke, air cooled, direct injection, compression ignition engine using Mahua oil methyl ester and diesel as fuel. The main findings of their study showed that the specific energy consumption of Mahua methyl ester is found to be higher than that of diesel at all loads. This is due to the low heating value (39 MJ/kg) and high viscosity of biodiesel (4.39 mm^2/s) compared to neat diesel of 44 MJ kg and 2.6 mm^2/s respectively. At full load, the power loss was around 13% combined with 20% increase in fuel consumption with Mahua oil methyl ester. Moreover, exhaust gas temperature, smoke intensity, Hydrocarbon, carbon monoxide and NO_x emissions for diesel were found higher than Mahua methyl ester at all loads. For instance, emissions of Hydrocarbon, carbon monoxide, NO_x and smoke at full load were lesser compared to diesel by 20%, 26%, 4% and 15% respectively. The authors concluded that Mahua can be promoted as an alternative fuel for diesel either as a sole fuel or as a blended fuel with diesel which will be environmentally friendly in nature.

Anand et al. [173] investigate combustion, performance and emissions characteristics of neat karanji biodiesel and its methanol blend in a diesel engine. The study results showed that unburnt HC and carbon emissions were slightly higher for methanol–biodiesel blend compared to neat biodiesel at low load conditions. However, at higher load condition unburnt HC emissions are comparable for the two fuels and CO emissions and exhaust gas temperature decrease significantly to a maximum of 46.5% at full load condition. The exhaust smoke emissions follow the same trend as carbon monoxide emissions and a maximum decrease of 96.4% is obtained at 80% load condition. The nitric oxide emissions are significantly lower at all the load conditions and a maximum decrease of 37.3% is obtained at full load condition. They also reported that the maximum thermal efficiency increase of 4.2% due to 10% methanol addition in the biodiesel is seen at 80% load and 16.67 s^{-1} engine speed.

Ramadhas et al. [77] evaluated the engine performance and emissions of a diesel engine fueled with methyl esters of rubber seed oil. Their results showed that the lower concentrations of biodiesel blends found to improve the thermal efficiency. B_{10} biodiesel blend gives a good improvement in the brake thermal efficiency of diesel engine by about 3% at the rated load conditions. Same improvement has been drawn to emission, smoked density and brake specific fuel consumption when using B_{10}. However, with increase in biodiesel blends NO_x emission is also expected to increase since the NO_x emission formation is a highly temperature dependent phenomenon and the exhaust gas temperature increased as a function of concentration of biodiesel in the blend. The experimental results proved that the use of biodiesel (produced from unrefined rubber seed oil) in compression ignition engines is a viable alternative to diesel.

Pradeep and Sharma [174] presented the performance, emission and combustion parameters of a single cylinder diesel engine running on biodiesel from rubber seed oil and its blends with diesel. They found that brake thermal efficiencies were lower for biodiesel blends compared to diesel. Higher combustion duration and lower heat release rates were also recorded for biodiesel.

Usta [86,87] investigated the effect of tobacco seed oil methyl ester substitution for the diesel fuel. He found that brake power and the thermal efficiency have increased slightly. Moreover, the addition of tobacco seed oil methyl ester to the diesel fuel reduced CO and SO_2 emissions while causing slightly higher NO_x emissions without any engine modification and preheating of the blends. The author concluded that tobacco seed oil methyl ester can be partially (up to 25–30%) substituted for diesel fuel No. 2 at most operating conditions in terms of performance parameters and emissions without any engine modification.

Li et al. [14] compared the engine performance of *Eruca sativa gars* (ESG) biodiesel with conventional diesel. Their main findings showed that the most encouraging results are obtained with B_{100}. The measured harmful emissions such as HC and CO are reduced by 33.33%. However, there is an increase in energy consumption, CO_2 and NO_x emissions by about 10.15%, 10.71% and 13.21% respectively.

Prakash et al. [175] carried out performance and emission tests using diesel fuel and biodiesel blends obtained from Karanja oil. Among the blends, 20% karanja methyl estere showed better performance characteristics compared to other blends. The study observed better brake thermal efficiency BTE, brake specific fuel consumption BSFC, and indicated thermal efficiency (ITE). With regard to exhaust emissions, 20% blend slightly increased the NO_x due to the higher specific gravity of the fuel. Both the PM emission and smoke density were low.

Pandian et al. [176] Experimented Pongamia biodiesel–diesel blend in a twin cylinder direct injection compression ignition engine with exhaust gas recirculation EGR and dimethyl carbonate DMC as additive. The experimental results showed that EGR technology can be the most economic methodology to reduce the NO_x emission from the Pongamia biodiesel–diesel blend fueled engine. They have reported that 15% EGR could be the optimum rate where, about 25% reduction in NO_x emission was obtained from the above specified engine. Despite of biodiesel containing some oxygen inherently, the introduction of EGR caused about a 16.92% increase in smoke emissions. Therefore, to reduce the smoke emission, DMC was found to be the best additive. The smoke opacity was approximately restored to the value of the base fuel on addition of 10% DMC with the 15% EGR. The authors observed that the smoke reduction rate had a linear relationship with DMC percentage. Moreover, the addition of DMC to the fuel had significant effect on BSEC, BTE, and other emissions. For instance, the carbon monoxide CO and hydrocarbon HC emissions decreased when DMC was added. However, the addition of DMC with EGR caused an increase in both BSEC and BTE. The authors concluded that the 15% EGR with 10% DMC can be used together for the reduction of NO_x emission without any impact on smoke emission from a pongamia biodiesel–diesel blend fueled engine.

Prasad et al. [177] also study the possibility of NO_x reduction in the exhaust gas of DI diesel engine fueled with Mahua methyl ester (MME) along with exhaust gas recirculation. After the analysis of results, the authors concluded that 5% EGR is preferable along with MME as it gives low HC, NO_x and CO as well as improvement in thermal efficiency than the pure petroleum diesel operation.

No [2] reviewed the use of non-edible vegetable oil such as *Jatropha* oil (JO) biodiesel blends, Karanja oil (KO) biodiesel blends, Mahua oil (MO) biodiesel blends, Linseed oil (LO) biodiesel, Rubber seed oil (RSO) biodiesel, Cotton seed oil (CSO) biodiesel and Need oil (NO) biodiesel. He reported that a diesel engine without any modification would run successfully on a blend of 40% biodiesel blend without any damages to engine parts. In addition, the blends of biodiesel and diesel can replace

Table 14
Engine performance and emissions production of biodiesel fuel engine as compared to diesel fuelled engine.

Non-edible biodiesel type or its blends	Engine	Test condition	Engine performance analysis highest/lowest (vs. diesel)						Exhaust emission highest/lowest (vs. diesel)						References
			BSFC	BTE	BMEP	BSEC	FTP	EGT	NOx	UHC	CO	CO_2	SO_2	Others	
B_0,B_{20},B_{40},B_{60},B_{80},B_{100} (mahua oil)	Ricardo E6 engine, 1C	Constant 1500 rpm	Min 4.3%↑Max 41.4% ↑	Min 10.1–17.1%↓Max 24–25% ↑	–	–		Min 6%↑Max 16% ↑	17 and 50 ppm (6%↑)	–	Min 0.02%↓Max 0.2% ↓	–	–	Smoke number: Min 7.8%↓ Max 75% ↓	Raheman and Ghadge [171]
B_0,B_{10},B_{20},B_{50},$B_{75}$$B_{100}$ (rubber seed oil)	1C, DI, NA	Speed 1500 rpm	Max 12 % ↑	Max 28% ↑	–	–	–	Min 200 °C Max 690 °C	–	–	Min 0.13%↓Max 1.13% ↓	Min 2%↓Max 11.5 % ↑	–	Smoke density:Max 49↑	Ramadhas et al. [75]
B_{20},B_{40},B_{60},B_{100} (poon oil)	1C,DI,AC	Speed 1500 rpm	–	Min 23%↓Max 26.7% ↓	–	Min 8%↑Max 15%↑	–	Min 400 °C–↑ Max 450 °C↑	Min 4–32%↓	Min 0.25 g/kWhr↓ Max 0.795 g/kWhr ↑	Min 0.048 g/kWh↓ Max 0.39 g/kWh ↑	Min 1.8%↓Max 9.8% ↓	–	Smoke number: Min 0.3%↓ Max 4.3%↑	Devan and Mahalakshmi [103]
B_{10},B_{20},B_{30},B_{40} (*putranjiva roxburghii* oil)	Ricardo diesel engine, 1C	Speed 1000–3000 rpm	Min 236 g/kWh↑ Max 572 g/kWh↑	Min 11.2%↓Max 27.24% ↓	–	–	–	–	12–28 ppm	42–69 ppm	Min 0.003%↓ Max 0.022%↓	–	–	Smoke density Max 30 Hu↓Min 8 Hu↓Particulates: Max 31 mg/m^3↓ Min 72 mg/m^3↓	Haldar et al. [92]
B_0, B_{10},B_{20},B_{50},B_{100} (*eruca sativa gear* oil)	Fukuda light truck BJ1043V8JE6–2 of which engine model is CY4100Q	Speed 3200 rpm	Min 0.90%↑ Max 10.15%↑	–	–		–	–	Min 2.38%↑ Max 13.21%↑	Min −4.76%↓ Max −33.3↓	−33% ↓	Min 0.60%↑ Max 10.71%↑	–	Carbon emissions: Min −5.47%↓ Max −17.21%↓	Li et al. [14]
B_{10},$B_{17.5}$,B_{25} (tobacco oil)	Turbocharged, 4C,DI, NA	Speed 1500–3000 rpm	Min 280 g/kWh↑ Max 437.5 g/kWh↑	Min 0.272%↑ Max 0.292%↑	–	–	–	Min 220 °C↓ Max 550 °C↓	Min 180 ppm Max 500 ppm ↑	–	Min 100 ppm↓ Max 1600 ppm↓	–	Min 50 ppm↑Max 225 ppm ↓	–	Usta [86]
B_{20},B_{50},B_{100} (*jatropha curcas, pongamia pinnata, calophyllum inophyllum*)	3C, CI	Speed 1200–2200 rpm	Min 158 g/BHP-h↑ Max 220 g/BHP-h↑	–	–	Min 180.55 gms/BHP-hr↓ Max 193.03 gms/BHP-h ↓	Min 0.44–2.55 %↓ Max 0.88%↑		Min 4.15%↑ Max 22.5%↑	Min −2.73%↓ Max 32.28↓	Min 2.59%↑ Max 35.21%↑	–	–	Smoke number: Min 1.29%↓ Max 65%↓Particulates: Min 16.43%↓Max 42.06%↓	Sahoo et al. [168]
B_{20},B_{40},B_{60},B_{80},B_{100} (polanga oil)	1C, WC, DI	–	–	0.1%↑	–	–	–		4%↓	–	–	–	–	Smoke number: 35% ↓	Sahoo et al. [8]
B_5,B_{10},B_{15},B_{20},B_{30}, (karanja oil)	Petter Kirloskar diesel engine 2C,WC	Speed 1500 rpm	Min 0.313 kg/kWh↑ Max 0.3190 kg/kWh↑	24.87%↓	–	–	–	332.2 °C↑	12%↑	Min 90 ppm↑Max 120 ppm↑	Min 0.15%↓Max 0.21% ↑	–	–	–	Srivastava and Verma [149]

Non-edible biodiesel type or its blends	Engine	Test condition	Engine performance analysis highest/lowest (vs. diesel)					
			BSFC	BTE	BMEP	BSEC	FTP	EGT
Jatropha oil methyl ester (JOME), honge oil methyl ester (HOME), sesame oil methyl ester (SOME) oil	1C, DI, WC, and CI engine	Speed 1500 rpm	–	Min 29%↓ Max 30.4%↓	–	–	–	
B_{10},B_{20},B_{30},B_{50}, B_{100} (linseed, mahua, rice oil, linseed oil methyl ester (LOME))	1C, WC, DI	Speed 1500 rpm	–	0% −30%	–	Min 15 kJ/hr/kw × 10^3↑ Max 40 kJ/hr/kw × 10^3↑	–	
B_{20},B_{40},B_{50},B_{60},B_{80},B_{100} (karanja oil)	AV-1, 1C, DI, CI, WC	Speed 1500 rpm	Oil without preheating: Min 400 g/kWh↓ Max 900 g/kWh%↑ Oil with preheating	Oil without preheating: 0–25% Oil with	–	Oil without preheating: Min 17 MJ/kWh↓ Max 34 MJ/kWh↑ Oil with preheating Min 15 MJ/kWh↓ Max 30 MJ/kWh↓	–	Oil with and without preheating: Min 220 °C↑ Max 570 °C↑

Table 14 (*continued*)

Non-edible biodiesel type or its blends	Engine	Test condition	Engine performance analysis highest/lowest (vs. diesel)					
			BSFC	BTE	BMEP	BSEC	FTP	EGT
			Min 400 g/kWh↓ Max 790 g/kWh%↓	preheating: 0–27%				
B_{50} (sesame oil)	Lombardini 6 LD 400, 1C, AC,DI	Speed 1300–3300 rpm	Min 380 g/kWh↑ Max 500 g/kWh↑	–	–	–	–	Min 90 °C↓ Max 180 °C↓
B_{20},B_{100} (karanja oil methyl ester (KOME), karanja oil ethyl ester (KOEE))	Kirloskar NA, 1C, DI	Speed 1500 rpm	Min 0.28 kg/kWh↓ Max 0.6 kg/kWh↑	Min 0%↓ Max 30%↓	–	–	–	–
B_5, B_{10}, B_{15}, B_{20} (karanja oil)	1C, DI	Speed 1500 rpm	–	Min 0.28%↓ Max 0.14%↓	–	Min 30000 kJ/kWh↓ Max 50000 kJ/kWh↓	–	–
B_{50}, B_{100} (methyl ester of paradise oil (MEPS))	1C, AC, DI	Speed 1500 rpm	–	26%↓	–	–	–	Min 140 °C↓ Max 450 °C↑
B_0,B_{20},B_{40},B_{60},B_{100} (methyl ester of mahua oil)	Turbocharged, AC, 6C	Speed 1500 rpm	Min 0.3 kg/kWh↑ Max 1.5 kg/kWh↑	Max 32.5%↑	–	Min 11000 kJ/kWh↑ Max 60000 kg/kWh↑	–	Min 7% (170 °C)↑ Max 12% (420 °C)↑

Exhaust emission highest/lowest (vs. diesel)						
NOx	UHC	CO	CO_2	SO_2	Others	References
Min 970 ppm↓ Max 1000 ppm↓	Min 60 ppm↑Max 67 ppm↑	Min 0.12%↑Max 0.155%↑	–	–	Smoke density: Min 62 HSU↑ Min 70 HSU↑	Banapurmatha et al. [182]
–	–	–	–	–	Smoke density: Min 5%↓ Max 88%↑	Agarwal et al. [129]
–	Oil without preheating: Min 3 g/KWh↓ Max 13 g/KWh↑ Oil with preheating Min 2.8 g/KWh↓ Max 10 g/KWh↑	Oil without preheating: Min 10 g/kWh↑ Max 530 g/kWh↑ Oil with preheating Min 40 g/kWh↑ Max 350 g/kWh↑	–	–	Oil without preheating: Min 5%↓ Max 98%↑ Oil with preheating Min 5%↓ Max 100%↑	Agarwal and Rajamanoharan [127]
Min 170 ppm↓ Max 780 ppm↑	–	Min 180 ppm↓Max 250 ppm↓	–	–	–	Altun et al. [179]
Part load 10%–25%↓	–	–	–	–	Smoke density: Min 1%↑ Max 13.9%↑	Baiju *et al.* [180]
Min 510 ppm↑ Max 2445 ppm↑	Min 13 ppm↑ Max 61 ppm↑	Min 0.05%↓Max 0.87% ↓	–	–	Smoke density: Min 2%↑ Max 44%↑	Bajpai et al. [181]
Min 5%↑ Max 8%↑	Min 22%↓Max 27% ↓	–	–	–	Smoke density: Min 33%↓Max 40%↑	Devan and Mahalakshmi [238]
11.6%↑	Min 23 ppm↓Max 66 ppm↓	Min 0.02↓Max 0.16 %↓	–	–	–	Godiganur [183]

Non-edible biodiesel type or its blends	Engine	Test condition	Engine performance analysis highest/lowest (vs. diesel)					
			BSFC	BTE	BMEP	BSEC	FTP	EGT
B_{10},B_{20},B_{30},B_{40} koroch seed oil methyl ester (KSOME)	1C, NA	Speed 1500 rpm	Min 0.3285 kg/kWh↑Max 0.3794 kg/kWh ↑	Min 22.32%↑ Max 25.63%↑	–	–	–	–
B_{10},B_{20},B_{30},B_{40} (soapnut oil (SNO))	1C,CI, WC	Constant speed: 1500 rpm	–	Min 1%↓ Max 27%↓	–	Min 4%↑Max8% ↑	–	–
B_{20},B_{100} (rice bran, *Pongamia pinnata* oil)	1C,DI, WC	Constant speed: 1500 rpm	Min 3.2% Max 16.8%↑	Min 4.9%↑ Max 6.8%↑	–	–	–	Min 18.3%↑ Max 27% ↑
B_{20},B_{40} (karanja oil)	AVL 1C,DI, WC,CI	Constant speed: 1500 rpm	–	–	–	Min 1.9%↑Max7% ↑	–	–
Linseed methyl ester (LOME)	Kirloskar 1C, AC, CI	Speed 1500 rpm	Min 3.7 MJ/kWh↑ Max 7 MJ/kWh↑	Min 14.2%↑ Max 27.5%↑	–	–	–	–
B_{20},B_{40},B_{60},B_{80},B_{100} (karanja oil)	1C, WC, CI	Speed 3000 rpm	Min 0.8–7.4%↓ Max 11–48%↑	Max 22.71% – 26.79% ↑	–	–	–	Min 260 °C↓Max 336 °C ↑
B_{20},B_{40},B_{60},B_{80},B_{100} (p*ongamia pinnata* methyl ester (PPME))	Kirloskar 1C, WC, CI	Constant speed: 1500 rpm	Min 0.3 kg/kWh↑ Max 0.82 kg/kWh↑	–	–	Min 3%↓Max8% ↑	–	Min 80 °C↓ Max 210 °C↓

Exhaust emission highest/lowest (vs. diesel)						
NO*x*	UHC	CO	CO_2	SO_2	Others	References
–	–	–	–	–	–	Gogoi and baruah [237]
Min 10%↓Max 35%↓	Min 25 ppm↑Max 90 ppm↑	Min 0.2%↑ Max 0.6%↑	–	–	Smoke density: Min 8%↓Max 78%↑	Misra and Murthy [42]
Min 10.8%↑Max 28.6%↑	Min 14.7%↓ Max 43.2% ↓	–	–	–	Smoke density: Min 33.8%↑Max 43.2% ↑	MohamedMusthafa et al. [184]
Min 28% Max39 %	Min 3% Max 12.8 %	–	–	–	–	Nagarhalli [187]
–	Min 10 ppm↓Max 47 ppm↓	Min 0.01%↓ Max 0.03%↓	–	–	Smoke density: Min 0.64 BSU↓Max 2 BSU ↑	Puhan et al. [185]
26%↓ (4–12 ppm)	–	Min 73%↓(0.004%) Max 94%↓(0.016%)	–	–	Smoke density: Min 20%↓(1%) Max 80%↓(3%)	Raheman and Phadatare [186]
Min 48 ppm↓Max 230 ppm ↓	1 ppm↓	Min 0.0005%↓ Max 0.3%↑	Min 0.05%↓ Max 2.9 %↓	–	–	Sureshkumar et al. [188]

Engine codes: NC=no. of cylinder; DI=direct injection; IC=intercooled; AC=air-cooled; WC=water-cooled; TC=turbocharged; NA=naturally aspirated; CI=compression ignition.
Performance analysis codes: BSFC=brake-specific fuel consumption; BTE=brake thermal efficiency; EGT=Exhaust gas temperature ; BMEP=brake mean effecitive pressure; BSEC=brake spesific energy consumption; FTP=full thorttle performance.
Exhaust emissions analysis codes: NO*x*=nitrogen oxide; UHC=unburn hydrocarbon; CO=carbon monoxide; CO_2=carbon dioxide; SO_2=sulfate dioxide; HSU=hartridge smoke unit; BSU=bosch smoke unit.
Highest=↑
Lowest=↓

the diesel fuel up to 10% by volume for running common rail direct injection system without any durability problems. They pointed out that most regulated emission, such as those of HC, CO and PM were reduced through the use of biodiesel and its blends. However, an increase in NO_x emissions has been reported through the use of biodiesel and its blends as a fuel in CI engine.

In this paper, a summary of engine performance and emissions productions for various non-edible biodiesel and blends has been presented in Table 14 [3,7,8,14,42,75,86,92,103,127,129,171,173,178–188]. Moreover, some alternative biodiesel feedstock which have been engine-tested have been highlighted by Razon [38].

11. Conclusion

Recently, biodiesel has become more attractive because of its economic and environmental benefits. Production of biodiesel from non-edible oil resources can play a vital role in helping to overcome the land problem as its can be grown in marginal and waste land areas for high yield. Moreover, the issue of food versus fuel for edible oil sources will make non-edible oil feedstocks as alternative fuels for diesel engines. Therefore, the demand for non-edible oil sources is expected to increase sharply in the near future. Some of non-edible feedstocks for biodiesel production include *Jatropha curcas*, *Pongamia pinnata*, Rubber seed, *Madhuca indica*, *Calophyllum inaphyllum*, *Sterculia feotida*, etc. However, it must be pointed out that global biodiesel feedstocks should not rely on certain sources as it could bring harmful influence in the long run. The worlds' dependence on fossil fuels is a perfect example. Therefore, biodiesel feedstock should be as diversified as possible, depending on geographical locations in the world.

In this review, numerous aspects linked to non-edible oil feedstocks such as non-edible oil resources, advantages of non-edible oils, problems in exploitation of non-edible oils, fatty acid composition profiles (FAC) of various non-edible oils, oil extraction techniques, technologies of biodiesel production, properties and characteristic of non-edible biodiesel and engine performance and emission characteristics have been studied.

The determined properties beside the engine performance and emission characteristics of non-edible biodiesel covered in this review indicated that there is a huge chance to produce biodiesel from non-edible sources in the future.

Acknowledgment

The authors would like to acknowledge the Ministry of Higher Education of Malaysia and The University of Malaya, Kuala Lumpur, Malaysia for the financial support under UM.C/HIR/MOHE/ENG/06 (D000006-16001).

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